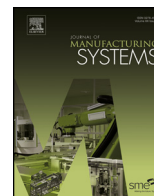




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A fuzzy goal programming model to strategic planning problem of a lead/acid battery closed-loop supply chain

Kemal Subulan, A. Serdar Taşan, Adil Baykasoğlu *

Dokuz Eylül University, Faculty of Engineering, Department of Industrial Engineering, Izmir, Turkey

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ABSTRACT

Economical, environmental and governmental considerations have forced the lead/acid battery manufacturers to build-up an effective and efficient spent battery collection and recovery systems. The design and implementation of such a collection and recycling system is affected by the distribution, collection and recycling facilities' location decisions which are strategic and important. A fuzzy multi-objective, multi-echelon and multi-product mixed integer linear programming model with different importance and priorities are developed in this paper. In contrast to the existing multi-objective closed-loop supply chain network design models which are generally cost or profit oriented, a new objective namely "maximization of the collection of returned batteries covered by the opened facilities" is also taken into account. Since the lack of flexibility issues in most of the supply chain planning models, new flexibility objectives such as total recycling and collection volume flexibility are also introduced due to the nature of reverse flows. Fuzzy goal programming model with different importance and priorities is used to solve the developed model. Furthermore, a novel approach for obtaining the desirable achievement degree of each fuzzy goal is proposed based on "weighted geometric mean" for group decision making procedure in which the importance/weights and the index of optimism of each group member are different. The proposed model is applied to an illustrative example based on inspiration from the lead/acid industry in Turkey. Solution of the proposed model is achieved by using ILOG OPL Studio version 6.3. Sensitivity analysis of the proposed model is also presented by considering different scenarios.

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1. Introduction

The increasing numbers of automobiles, trucks, motorcycles on roads as well as boats, marine crafts and several industrial applications have caused continuously increasing demand for lead/acid batteries. Nowadays, along with these demand increments and some difficulties encountered in Turkey, such as the lack of producing pure lead economically from the primary sources and prohibition on import of scrap batteries have made Reverse Logistics (RL) activities and battery recycling important issues in the lead/acid battery industry. Furthermore, as a result of providing the large part of industrial lead requirements through imports with highly purchasing costs instead of producing pure lead from the primary sources, the battery manufacturers have been forced to obtain lead by using secondary sources and to build-up an effective

and efficient spent battery collection and recovery systems. In addition, according to the Battery Council International, lead/acid battery recovery systems have an environmental success story; more than 97% of all battery lead can be recycled. This rate is quite high when compared to 55% of aluminium soft drink and beer cans, 45% of newspapers, 26% of glass bottles and 26% of tires. Also, the recyclable components of lead/acid batteries such as lead and plastics can be recycled so many times [1]. From the perspective of the health and environmental aspects, spent lead/acid batteries consist of lead, lead compounds, and sulphuric acid, all of them are very toxic and hazardous. Therefore, scrap lead/acid batteries are classified as hazardous waste under the Hazardous Waste Act – 1989 and should not be disposed of in ordinary garbage. Lead is a cumulative poison in human's body and also harmful to the environment, particularly fish, animals and plants. The electrolyte in batteries is corrosive and can cause loss of eyesight and skin damages if the battery explodes. Moreover, the plastic parts such as polypropylene casing (box) is not biodegradable and it is appropriate for recycling. Therefore, spent batteries should be recycled into new ones made from the lead, sulphuric acid and polypropylene since using less energy than refining primary ore and removes lead from the

* Corresponding author. Tel.: +90 2323017600; fax: +90 2323017608.

E-mail addresses: kemal.subulan@deu.edu.tr (K. Subulan),

serdar.tasan@deu.edu.tr (A.S. Taşan), adil.baykasoglu@deu.edu.tr,

baykasoglu@gmail.com (A. Baykasoğlu).

environment [2–4]. Both these economical and environmental issues with the legal obligations have a pressure on battery manufacturers and all other stakeholders of lead/acid battery supply chains to manage the reverse flows of the used batteries. The design and implementation of an effective and efficient collection-recovery system are affected by the distribution, collection and recycling facilities' location decisions which are strategic and essential. Since the strategic planning problem is crucial for the lead/acid battery sector and the multi-objective Closed-Loop Supply Chain (CLSC) network design models have been rarely discussed in the literature; in this study, a fuzzy multi-objective linear programming (FMOLP) model with different importance and priorities is proposed for the network design problem of a lead/acid battery CLSC.

In the proposed model, both forward–reverse flows and their mutual interactions are considered simultaneously in an integrated model with the environmental and cost perspectives mentioned above. Uster et al. [5] highlighted that RL networks which are independent of the forward flows will cause accretion in infrastructure costs and potential profit reduction related to the recovery option such as recycling, remanufacturing etc. Therefore, optimal network design requires the consideration of forward and reverse flows simultaneously. The proposed model decides physical locations of distribution centres, collection centres, hybrid facilities and licensed recycling facilities. Furthermore, production, collection, recycling, transportation and purchasing quantities can be determined for both scrap batteries and materials/components.

The main purpose of this research is to develop a multi-objective, multi-echelon and multi-product strategic planning model for the lead/acid battery CLSC. Fuzzy goal programming approach with different importance and priorities (FGP-DIP) which was developed by Chen and Tsai [6] is used to solve the proposed model. In the proposed model, minimization of the total cost of CLSC which consists of fixed investment costs, production costs, transportation costs, purchasing costs regarding materials/components and spent batteries, recycling costs, collection costs and disposal cost; maximization of the collection of returned batteries covered by the opened collection centres and/or hybrid facilities; and finally maximization of the total volume flexibility that includes manufacturing–recycling and distribution–collection volume flexibilities are addressed as the objective functions. Although flexibility is an important part of the performance measurement system for a supply chain configuration, this concept has not been sufficiently addressed and modelled in the literature so far. Two different flexibility categories namely volume flexibility and delivery flexibility were expressed by Slack [7] and Sabri & Beamon [8]; defined as “the ability to change the level of produced products and planned delivery dates”. In other words, volume flexibility refers to capability of changing the volumes of production, distribution, recycling etc. and can be measured as the difference between capacity and capacity utilization. In practice, one can measure the volume and delivery flexibilities by utilizing capacity and lead time slacks, respectively. In fact, these two different flexibility types match up with the process flexibility and logistics flexibility which were stated as the two main aspects of supply chain flexibility by Sanchez and Perez [9]. In addition, these flexibility aspects were incorporated into the three flexibility dimensions as follows [9]: (i) Basic (shop-floor) flexibility which consists of product, volume and routing flexibilities, (ii) system (company) flexibility that handles delivery, transshipment and postponement flexibilities and finally (iii) aggregate (chain) flexibility which includes launch, sourcing, response and access flexibilities. It is also noted by Vickery et al. [10] that flexibility is a significant concept for measuring supply chain performance and may be an opportunity to improve firms' efficiency and sustainability. Therefore, we focused on the volume and access flexibilities in this paper. The third objective

function represents the total volume flexibility which generally consists of plant/manufacturing and distribution volume flexibilities. In addition, recycling and collection volume flexibilities were also incorporated within this total volume flexibility. Moreover, the access flexibility which means the ability to provide an extensive distribution and collection coverage was also realized in the second objective function.

This paper is organized as follows. The literature related to the RL & CLSC network design problems are given in Sections 2.1 and 2.2, respectively. Details of the problem with the notation, model parameters, decision variables and mathematical model formulation are described in Section 3. In Section 4, the proposed model is applied to a case study inspired from lead/acid battery sector in Turkey for depicting the validity and practicality of the proposed model and efficient compromise solution of the proposed model with the satisfaction of multiple fuzzy goals is achieved by using ILOG OPL Studio version 6.3. Section 5 demonstrates the fuzzifying of the proposed strategic planning model and contains the construction of the membership functions, determination of the desirable achievement degrees for all fuzzy objectives by using linguistic variables and transformation of the fuzzy model to the equivalent crisp mathematical formulation. Sensitivity analysis of the proposed model is also presented considering different scenarios in Section 6. Finally in Section 7, conclusion and future works are given.

2. Literature review

Literature survey is distinguished in two main topics as RL & CLSC network design and multi-objective optimization in RL & CLSC environment. The main properties, advantages and disadvantages of RL & CLSC network design, solution approaches to these network design problems such as mixed integer programming, decomposition methods and heuristic based methodologies and finally modelling approaches for uncertainty such as stochastic, possibilistic etc. are given as subtopics in Section 2.1. In Section 2.2, multi-objective optimization techniques such as ϵ -constraint method, bounded method and goal programming method etc. which are applied in RL & CLSC network design are reviewed. Then, literature review on the application of FGP-DIP in different research areas are mentioned and finally other FGP techniques such as weighted additive method, interactive FGP etc. which are used in RL & CLSC network design are discussed.

2.1. Literature review on RL & CLSC network design

RL and CLSC have becoming important issues for both researchers and practitioners in the last decade because of the increasing competition, regulatory pressures and customer expectations. In contrast to RL, CLSC involves not only the reverse flows of the materials/goods from the end users to the manufacturers or related facilities such as collection centres, disposal sites and recovery centres but also the forward flows of raw materials/goods from suppliers to manufacturers and then to customers.

CLSC covers traditional forward supply chain activities with the additional activities related to the reverse flows. These activities can be explained as follows [11]: (i) collection/acquisition of used products from the end-users, (ii) transportation and also warehousing of these used products from the points of use to a point(s) of disposition, (iii) classification, controlling and inspection in order to determine the product's condition for selecting the most economic or the best recovery option, (iv) selection of the right recovery option: direct reuse, refurbish, repair, remanufacture, recycle or disposal, (v) sales and distribution of these refurbished products to the new or secondary markets.

As mentioned above, RL activities have been included as an important issue in a CLSC. Some important properties, advantages and disadvantages of the RL & CLSC network design can be summarized as follows. In fact, RL & CLSC network design is applicable for the remanufacturable/refurbishable products that have high recoverable value, long product life cycles and well-established forward flows [5]. It is also an important step for development of sustainability which interests both economics aspects and the other aspects such as environment and sustainability of natural resources [12]. Moreover, effective and efficient RL activities can increase companies' customer service levels and constancy of the existed customers while reducing their costs such as acquisition, production, disposal, inventory and transportation costs. Additionally, the environmental side of RL activities enforces company to gain new customers with environment consciousness [13]. In addition to all of these, designing the logistics network as a strategic decision provides the inputs of the tactical and operational decisions [14]. On the other hand, in CLSCs, integrating the forward and reverse channels is a challenging task and important part of the decision making process [15]. Because, integrated network design problems (CLSC) act like a combinatorial problem whose computation time to yield an optimal solution increases exponentially when the problem size grows [16]. Furthermore, complexity in CLSC is generally higher than the open loop supply chains [17].

Major classifications related to the RL and CLSC management are made by [18] and [19]. This research area can be divided into three important topics namely distribution, production planning and inventory when looked from the perspective of operations research [18]. In terms of RL and CLSC network design, the problem type is classified into two groups as deterministic and stochastic and evaluated by [19] under the topic of RL & CLSC in the literature of environmentally conscious manufacturing and product recovery. They emphasized that the most of the related deterministic studies take into account the only reverse flows with the modelling technique of mixed integer programming. For instance, Fleischman [20] proposed the most generic recovery network model in order to determine the number of facilities, their locations, amounts of both forward and reverse flows and then used mixed integer linear programming optimization technique. This generic model was extended by [16] adding more realistic conditions such as planning period and various transportation modes. Salema et al. [18] reformulated this generic model while taking into account the production/storage capacities of opened facilities, multiple product production and uncertainty related to the amounts of customers' demand and product returns by employing multiple-scenario based approach. Pishvaei et al. [21] developed a stochastic programming model for a CLSC network design by using scenario-based stochastic approach. In that paper demands, the quantity and the quality of returns and the variable costs were considered as uncertain parameters. A mixed integer linear programming model was developed by Demirel and Gokcen [22] for a multi-echelon, multi-product deterministic CLSC network design considering remanufacturing recovery option in order to locate disassembly, collection and distribution facilities. Sasikumar et al. [23] formulated a mixed integer non-linear programming model for maximizing the overall profit of a multi-echelon, multi-period RL network with a real life case of truck tire remanufacturing while taking into account secondary market requirements. Subulan and Tasan [24] extended the previously mentioned RL network design model developed by [23] for end of life tires by integrating the forward flows and considering different recovery options simultaneously such as remanufacturing, recycling and energy recovery for a more holistic CLSC network design problem. Configuration of a CLSC network based on the product life cycle is provided by Amin and Zhang [17] via mixed integer linear programming technique, in detail three return/recovery pairs namely commercial,

end-of-use and end-of-life are taken into account in the design phase. Another deterministic mathematical model that considers three recovery options: disassembly, recycling and repairing is proposed by Dat et al. [25] for RL network design of waste electrical and electronic products which track different recycling process based on its characteristics. Das and Chowdhury [26] developed a mixed integer linear programming model for a CLSC planning with modular design architecture and different quality levels of sold products to the markets with the objective of overall profit maximization.

Due to the undesired long computational time and bad solution quality of large scale or real life RL & CLSC network design problems, some researchers used heuristic based approaches or decomposition methods as a solution methodology. For instance, an efficient dual problem solution method based on Benders decomposition with multiple Benders cuts was proposed by Uster et al. [5] to solve a mixed integer linear programming model for a real life CLSC network of an OEM in the automotive industry. Since the RL network design pertains to a class of NP-complete problem [27], Min et al. [28] used genetic algorithm to solve the proposed non-linear mixed integer programming model for a RL network design which aims to locate initial collection points and centralized return centres. A priority based genetic algorithm was proposed by Lee et al. [29] for a multi-product, three stage RL network design problem. Extended version of the generic recovery model was solved by [16] by using linear programming (LP) based genetic algorithm. A genetic algorithm based heuristic was proposed by [30] for solving the developed multi-echelon, multi-product and multi period CLSC network design model for a battery recycling case. Results showed that their proposed methodology provides better outcomes in terms of quality of solutions and computational time for the larger scale problems, where commercial software like GAMS cannot provide any feasible solutions.

Uncertainty in timing, quality and quantity of product returns is an important aspect of RL and CLSC network design problems. As mentioned by [19], this issue can be handled by using robust optimization technique in stochastic RL network design models. However, development of dynamic, probabilistic and stochastic RL & CLSC and production-distribution planning models is still investigated by relatively few researchers as mentioned by Fahimnia et al. [31]. Thus, they expressed the development of these types of models as the future research trends. A two-stage stochastic programming model was proposed by Kara and Onut [32] for single product, two-echelon capacitated RL network design in waste paper recycling industry in order to maximize revenue. Demand and amounts of collected products are assumed as uncertain and fitted to the normal distribution while generating alternative scenarios. Lee et al. [12] also proposed a two-stage stochastic programming model for sustainable logistics network design. Demands of forward products and the supply of returned products are assumed to be stochastic parameters which have known distribution. Because of the some disadvantages of the stochastic programming such as difficulty related to availability of historical data and complex modelling, uncertain demand and purchasing cost in strategic agile CLSC network design problem of perishable goods was handled via interval robust optimization technique by Hasani et al. [33]. Uncertain demands, returns, delivery times, costs and capacities were taken into account by using possibilistic programming approach by Pishvaei and Torabi [34] in a CLSC network design problem which integrates strategic and tactical planning decisions. Subulan et al. [35] developed a fuzzy mixed integer programming model with non-linear constraints for medium-term planning in a CLSC with remanufacturing option. In their proposed model, storage capacities, retailers' and wholesalers' demands, return rates, acceptance ratios, weekly available production/remanufacturing times, transportation upper bounds and objective function value are considered as fuzzy. A

Table 1
Multi-objective RL & CLSC network design models.

Article	Goals	Method
Du and Evans [13]	Minimization of the overall costs and minimization of total tardiness of cycle time	Combination of Scatter Search, Constraint Method and Dual Simplex Method
Pishvae and Torabi [34]	Cost minimization and minimization of total tardiness	Interactive Fuzzy Solution Approach
Wang, Lai, and Shi [36]	Minimization of total cost and minimization of the total CO ₂ emissions	Normalized Normal Constraint Method
Mirakhorli [38]	Minimization of total cost and total transportation time of the system	Interactive Fuzzy Goal Programming
Khajavi, Seyed-Hosseini, and Makui [39]	Cost minimization and maximizing the responsiveness of configuration	Bounded Method
Zegordi, Eskandarpour, and Nikbakhsh [40]	Minimizing fixed and transportation costs and total weighted tardiness of returned products	ε -Constraint Method
Pati et al. [41]	Minimizing RL costs, minimizing the non-relevant waste paper and maximizing the wastepaper collection	Goal Programming
Nukala and Gupta [42]	Maximizing net profit, maximizing revenue obtained from recycling and minimizing disposed items	Weighted Additive Method
Zarandi, Sisakht, and Davari [43]	Minimizing total cost, maximizing total service level and maximizing reverse service level	Interactive Fuzzy Goal Programming

mixed integer non-linear programming model was developed by Tabrizi and Razmi [36] for designing a multi-echelon, multi-source, multi-commodity and multi-capacity supply chain network under uncertainty. They utilized fuzzy set theory for managing the uncertainties threatened by the different risk sources.

2.2. Literature review on multi-objective RL & CLSC network design and applications of FGP-DIP

In the real life applications of RL & CLSC network design, instead of one objective as in the traditional linear programming models, there may be several conflicting objectives and this is more realistic. However, it is emphasized that supply chain network design problem is generally modelled as a single objective problem in the literature. In other words, there are a lot of studies in RL & CLSC management using various techniques but so little use the multi-objective optimization [37,38]. Some of the multi-objective models are presented in Table 1.

Goal programming is an important member of the multi-objective optimization family. In goal programming models, decision maker (DM) determines the target value or achievement level for each goal. On the other hand, determination of these target values in a definite way or implicitly is generally a difficult task for the DMs since the lack of some information or uncertainty. Therefore, goals should be stated imprecisely in the case of fuzzy decision environment such as RL & CLSC network management/design environments. In order to reflect the real life situations better, the issue of uncertainty should be taken into account in a typical RL & CLSC network design problem as it is a strategic/long-range decision making problem with many uncertainties. Various operations research techniques are available for handling the uncertainty like stochastic programming, robust optimization, possibilistic programming and fuzzy optimization.

Assessments and measurement of the total cost (in this study, objective-1) is a challenging task and requires a great deal of human perception. The objective value (total cost) becomes fuzzy in character because of the fuzzy cost items such as production, transportation, collection, recycling etc. which constitute the total cost [44]. In addition, with the perspective of second objective (maximization of the collection of used batteries) since the quantities of returned batteries can be calculated through an uncertain fraction of dealer's forecasted demand and the some information is incomplete or unobtainable regarding these parameters, this objective value should also be fuzzy. Finally, we consider manufacturing plants', licensed recycling facilities', depots' capacities and related

weight factors for capacity utilizations while calculating the total volume flexibility in the third objective function as fuzzy parameters. Baykasoğlu and Göçken [45] referred to these models with fuzzy objectives as type-1 fuzzy mathematical programming models in their extensive classification.

In this paper, a FMOLP model with different importance and priorities is presented by employing an approach which was developed by [6]. Chen and Tsai [6] incorporated the different importance and preemptive priority structure of the decision maker into a single formulation by using an additive model with the objective of maximizing the sum of achievement degrees of all fuzzy goals. Some of the formerly developed FGP techniques are briefly discussed next.

FGP approach was firstly introduced by Narasimhan [46] with the usage of membership functions and min-operator based on fuzzy mathematical programming approach in [47] for multi-objective optimization problems. In that model, objective function was to maximize the membership function value of least satisfied goal or constraint where there is no fundamental difference between them. An important issue in FGP problems is the reflection of the importance weights and satisfaction sequence or achievement order of some goals since they may be different for the decision makers. Linguistic terms such as 'important', 'very important', 'low important' and so on were used in [46] to verbally define the relative importance of each fuzzy goal. By contrast, Twiari et al. [48] added the weights of each goal in the objective function as coefficients in order to consider this relative importance. The main disadvantage of these former methods is the computational efficiency reduction in the case of an increase in the satisfaction sequences/orders (priority levels) of the goals. This was one of the main reasons for reformulation of the FGP by Chen and Tsai [6]. They removed this drawback and obtained more efficient solutions by expressing the desirable achievement degrees of each fuzzy goal precisely in order to provide single formulation for priority structure. They assigned higher achievement degrees to the more important goals by using linguistic variables. Comparisons showed that obtained sum of the satisfaction degrees from that method of [6] is greater than the other ones and has more computational superiority. This is the main reason for preferring this method for the present study. However, one of the drawbacks of this method is the possibility of resulting infeasible solutions in the case of determining very high desirable achievement degrees for the goals. In such a situation, a compromise solution between goals should be made by the DM or modification of the membership functions or model parameters may be required until satisfactory solution is

Table 2
Applications of FGP technique developed by Chen and Tsai [6].

Article	Objectives Fuzzy in Character	Application Study
Jamalnia and Soukhakian [50]	In addition to the objectives in [50], a qualitative objective – maximizing the customer satisfaction from the company operations	Non-linear aggregate production planning with learning curve effects
Belmokaddem, Mekidiche, and Sahed [51]	Minimization of total production costs, minimization of inventory holding costs and minimization of changes in workforce level	Aggregate production planning of an iron manufacturer
Tsai, You, Lin, and Tsai [52]	Maximizing net profits, minimizing the rate of end users' claims and minimizing the rate of late lading	Allocation of steel products among multiple distribution channels
Chen and Weng [53]	Achieving the maximum satisfaction degree of several goals in product design phase	Determination of necessary fulfilment levels of design requirements in QFD

provided. It is clearly understood that determination of these desirable achievement degrees is a difficult task. The approach which was proposed by Liou and Wang [49] is usually employed to determine the desirable achievement degrees precisely by [50,51] in the case of only single decision maker.

There are a few studies in the literature that represent the application of FGP-DIP developed by Chen and Tsai [6] and to the best of our knowledge, there is no study which presents the application of this method in a RL & CLSC environment so far. Some of the available studies are summarized in Table 2 and then other FGP methods including RL & CLSC topic are mentioned next:

There are a few applications of other FGP methods in RL & CLSC environment. For instance, application of weighted additive method which was developed by [48] was presented by [42] for strategic and tactical planning of a CLSC network where the aspiration levels of three goals namely maximizing the net profit, maximizing the revenue from recycling and minimization of disposed items were imprecise.

A solution methodology based on the combination of the three algorithms: scatter search, the constraint method and dual simplex method was designed by [13] for a multi-objective post-sale service CLSC network design model. Goals of their model were the minimization of the overall costs and the minimization of the total tardiness of cycle time. Zarandi et al. [43] extended the study of [54] by adding backward flows in order to analyze the effects of reverse costs and backward service level. They considered three goals with fuzzy aspiration levels: minimizing total cost, maximizing total service level and maximizing the reverse service level and solved the problem through interactive FGP approach. Interactive FGP approach was also used by Mirakhorli [38] to solve the multi-objective RL network design problem which also assumes that the demand and amounts of returned products were imprecise and represented by fuzzy triangular numbers. In addition to the minimization of total cost, the minimization of total transportation time was considered as an objective which is used for measuring customer satisfaction.

3. Model development

3.1. Problem description and assumptions

Lead/acid battery sector requires an optimal design for the CLSC network. The general scheme of the CLSC network structure is shown in Fig. 1. In this study, not only “opening of regional wholesalers for forward flows of newly produced batteries” and “the setting up of the collection centres for reverse flows”, but also “a hybrid facility which undertake the transfer of both forward and returned batteries” are taken into account as in the model developed by [12]. Actually, hybrid facilities can perform both distribution and collection activities. Thus, the facilities that will be opened in the candidate locations have to be one of these three alternative facility types. In this case, hybrid facilities are both “regional wholesalers” which market the new batteries for meeting the customers' demand and “collection centers” which collect the spent batteries from the retailers or service outlets, store for up to several days and then send to the licensed recycling facilities.

In the forward supply chain, in addition to provide some materials from the recycling way, the main components of a lead acid battery such as battery pole posts, plate, metallic grid, lead oxide, electrolyte, polypropylene casing [30] are purchased from different vendors for new battery production. Once the battery is produced in different new battery manufacturers it has to be distributed via regional wholesalers or hybrid facilities to the dealers, retailers or authorized automotive services and then end users. In the reverse chain, the end user leaves the spent battery at the retailer or dealer where it is replaced by a new one at the end of battery use. Therefore, we can designate the retailers or dealers as initial collection points. Then the collected spent batteries are transported to the licensed recycling facilities through collection centres or hybrid facilities. Furthermore, collection centres and hybrid facilities can be considered as a temporary storage area for the returned batteries. Before transshipping to the licensed recycling facilities, used batteries are controlled in terms of quality specifications for recycling process. According to the controlling process, the useless

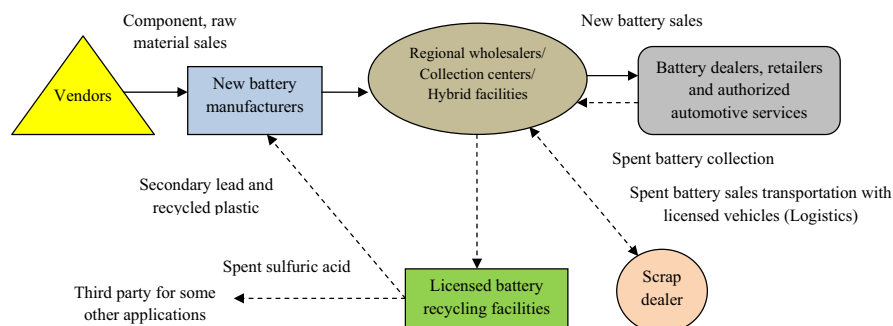


Fig. 1. A depiction of the CLSC network for the lead/acid battery recovery.

batteries are disposed off and the appropriate batteries for recycling are shipped to the licensed recycling facilities which are secondary lead smelters and plastic recyclers. In accordance with the need for spent battery, additional used batteries can be purchased from the scrap dealers which are certificated with temporary storage permission.

After the recycling process, the lead and plastic parts are transported to the new battery manufacturers where secondary lead and recycled plastic are used with the virgin lead and plastic. The spent sulphuric acid is sold to the third party for chemical production, fertilizer production, pigment production and pesticide industry etc. [30].

The proposed mathematical model will be developed based on the following assumptions: In the proposed model, decision makers have imprecise goals such as “total CLSC cost should be approximately less than some value”, “amounts of collected spent batteries should be approximately greater than some value” or “total volume flexibility should be greater than some value”. This imprecise nature is actually fuzziness rather than randomness. Therefore, aspiration levels of the goals are stated as fuzzy, constraints of the proposed model assumed to be crisp. Continuous linear membership functions are used for each of the objectives based on the payoff table. There are two different options for the new battery manufacturers to supply components such as lead, plastic etc. One is purchasing them from different suppliers; and the other is acquiring them by recycling from the licensed recycling facilities. Shortages and inventory holding are not allowable and cost parameters at all stages of the CLSC network do not change. The cost parameters at all stages are fixed on an annual basis. Inventory and backordering levels are not taken into account in the scope of strategic planning since they are generally considered in tactical and/or operational levels of CLSC planning. Transportation lead times between the stages are not taken into account because of the single period consideration which is a fundamental characteristic of strategic planning problems. Generally, transportation lead times can be considered in tactical and/or operational planning levels. Since annually aggregated demand forecasts are taken into account in the strategic planning level, the dealers’ or retailers’ demands are known and deterministic. Quantity of returned batteries from a given dealer or retailer is the fraction of total demand of that dealer or retailer. Any collection centre or hybrid facility can purchase additional scrap batteries from the scrap dealers for recycling in the case of need. Furthermore, this collection centre or hybrid facility can also sell a certain amount of their collected scrap batteries to the scrap dealers if it is cost advantage. However, purchasing and selling operation for same type of scrap battery cannot be performed simultaneously and at most one alternative can be done. On the other hand, these operations (purchases and sales) can be performed at the same time for different types of scrap batteries by the collection centre or hybrid facility. It is assumed that physical locations of scrap dealers have not an impact on the CLSC network design and they have an infinite capacity and budget for used battery sales or purchasing. Because, there are several scrap dealers with different scales and they have trade activities with the members of different lead/acid battery supply chains. In other words, there are many scrap dealers those can serve collection centres and hybrid facilities. The monetary value of a scrap battery does not change from one scrap dealer to another considerably. Therefore, locations of scrap dealers have not an impact on CLSC network design. According to the DMs, all flexibility components have the same importance/weight in the case study.

3.2. Indices and sets

b set of battery type $b \in B$
 c set of component type $c \in C$

i set of new battery manufacturers $i \in I$
 j set of potential depots such as regional wholesalers, collection centres or hybrid facilities $j \in J$
 k set of battery dealers, retailers or authorized automotive services $k \in K$
 l set of potential licensed recycling facilities $l \in L$
 v set of vendors $v \in V$

3.3. Model parameters

$f1_j$ fixed set-up cost of the regional wholesaler j
 $f2_j$ fixed set-up cost of the collection centre j
 $f3_j$ fixed set-up cost of the hybrid facility j
 $f4_l$ fixed set-up cost of the licensed recycling facility l
 PRC_b production cost of one unit of battery type- b in each new battery manufacturer
 TC_b transportation cost of one unit of battery type- b per kilometre
 $TC1_b$ transportation cost of one unit of used battery type- b per kilometre
 TC_c transportation cost of material/component type- c in kilograms per kilometre
 PUC_{cvi} purchasing cost of material/component type- c in kilograms from vendor v for manufacturer i
 PC_{bj} purchasing cost of one unit of used battery type- b from any scrap dealer for depot j
 SP_{bj} selling price of one unit of used battery type- b from depot j to any scrap dealer
 RC_{bl} recycling cost per unit of used battery type- b in licensed recycling facility l
 CC_b collection cost per unit of spent battery type- b
 DIC_b disposal cost per unit of un-recyclable battery type- b
 DE_{bk} demand of battery dealer or retailer k for battery type- b
 S_b returned fraction of demand for battery type- b from battery dealers or retailers
 a_{jk} binary parameter is equal to 1, if the distance between the battery dealer k and collection centre or hybrid facility j is within the maximum acceptable distance. 0, otherwise
 θ_b disposal rate for battery type- b
 γ_b recycling rate for battery type- b
 W_b weight of the used battery type- b
 ε_{cb} percentage of contribution of material/component type- c for the used battery type- b
 ρ_{cb} amount of material/component type- c to produce one unit of new battery type- b
 cap^f_{bj} capacity of regional wholesaler j for forward flows of newly produced battery type- b
 $hcap^f_{bj}$ capacity of hybrid facility j for forward flows of newly produced battery type- b
 cap^r_{bj} capacity of collection centre j for reverse flows of spent battery type- b
 $hcap^r_{bj}$ capacity of hybrid facility j for reverse flows of spent battery type- b
 $Prcap_{bi}$ production capacity of new battery manufacturer i for battery type- b
 $REcap_{bl}$ recycling capacity of licensed recycling facility l for used battery type- b
 $Vcap_{cv}$ supply capacity of vendor v for material/component type- c
 $d1_{ij}$ the distance between new battery manufacturer i and depot j
 $d2_{jk}$ the distance between depot j and battery dealer or retailer k
 $d3_{jl}$ the distance between depot j and licensed recycling facility l

d_{4li}	the distance between licensed recycling facility l and new battery manufacturer i
$DMAX$	maximum allowable distance from a given regional wholesaler or hybrid facility to a battery dealer or retailer for new battery distribution
$D1MAX$	maximum allowable distance from a given battery dealer or retailer to a collection centre or hybrid facility for used battery collection
$W1$	weight factor for capacity utilization of manufacturing plants
$W2$	weight factor for capacity utilization of regional wholesalers and hybrid facilities for performing forward flows
$W3$	weight factor for capacity utilization of licensed recycling facilities
$W4$	weight factor for capacity utilization of collection centres and hybrid facilities for performing reverse flows
N	maximum number of opened collection centres and hybrid facilities
M	an arbitrary set large number

3.4. Decision variables

w_j	1, if a regional wholesaler is opened at location j ; 0, otherwise
c_j	1, if a collection centre is opened at location j ; 0, otherwise
h_j	1, if a hybrid facility is opened at location j ; 0, otherwise
r_l	1, if a licensed recycling facility is opened at location l ; 0, otherwise
Q_{bi}	production quantity of battery type- b in new battery manufacturer i (units)
x_{bijl}	quantity of battery type- b shipped from new battery manufacturer i via regional wholesaler or hybrid facility j to the battery dealer k (units)
$x1_{bkjl}$	quantity of used battery type- b shipped from battery dealer k via collection centre j or hybrid facility j to the licensed recycling facility l
$x2_{cli}$	quantity of material/component type- c shipped to new battery manufacturer i from licensed recycling facility l (kg)
QP_{cvi}	amount of material/component type- c purchased from vendor v by new battery manufacturer i (kg)
q_{bjl}	quantity of used battery type- b purchased by depot j (Hybrid facility or collection centre) from any scrap dealer and sent to the licensed recycling facility l (units)
$q1_{bj}$	quantity of used battery type- b sold to any scrap dealer from depot j (units)
RE_{bl}	recycling quantity of used battery type- b at the licensed recycling facility l (kg.)
y_{jk}	1, if regional wholesaler or hybrid facility j serves battery dealer k for meeting its demand in the forward chain; 0, otherwise
$y1_{kj}$	1, if collection centre or hybrid facility j serves battery dealer k for collecting the returned batteries from this battery dealer in the reverse chain; 0, otherwise
y_{bj}	1, if depot j purchases used battery type- b from any scrap dealer; 0, otherwise
$y1_{bj}$	1, if depot j sells used battery type- b to any scrap dealer; 0, otherwise

3.5. Mathematical formulation of the problem

We proposed a multi-objective linear programming (MOLP) model with three objectives namely “minimization of the total CLSC cost”, “maximization of the collection of returned batteries through opened collection centres or hybrid facilities” as in the

well known maximal coverage problem and “maximization of total volume flexibility”. In order to be more decipherable, all flows on the network with the relational decision variables are displayed in Fig. 2.

The objective functions are defined as follows:

- (i) The first objective function is to minimize the total CLSC cost which is the summation of fixed opening costs (FOC), production costs (PC), transportation costs (TC), component purchasing costs (CPUC), scrap battery purchasing costs (SPUC), recycling costs (REC), collection costs (CC), disposal costs (DC) minus revenue obtained from the sales of collected scrap batteries (REV) as represented in Eqs. (1)–(10).

$$\text{Min } Z_1 = FOC + PC + TC + PUC + REC + CC + DC - REV \quad (\text{Goal}_1) \quad (1)$$

$$FOC = \sum_{j \in J} f1_j \cdot w_j + \sum_{j \in J} f2_j \cdot c_j + \sum_{j \in J} f3_j \cdot h_j + \sum_{l \in L} f4_l \cdot r_l \quad (2)$$

$$PC = \sum_{b \in B} \sum_{i \in I} Q_{bi} \cdot PRC_b \quad (3)$$

$$TC = \sum_{b \in B} \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{bijl} \cdot TC_b \cdot (d1_{ij} + d2_{jk}) + \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} x1_{bkjl} \cdot TC1_b \cdot (d2_{jk} + d3_{jl}) + \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} q_{bjl} \cdot TC1_b \cdot d3_{jl} + \sum_{c \in C} \sum_{l \in L} \sum_{i \in I} x2_{cli} \cdot TC_c \cdot d4_{li} \quad (4)$$

$$CPUC = \sum_{c \in C} \sum_{v \in V} \sum_{i \in I} QP_{cvi} \cdot PUC_{cvi} \quad (5)$$

$$SPUC = \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} q_{bjl} \cdot PC_{bj} \quad (6)$$

$$REC = \sum_{b \in B} \sum_{l \in L} RE_{bl} \cdot RC_{bl} \quad (7)$$

$$CC = \sum_{b \in B} \sum_{j \in J} \sum_{k \in K} y1_{kj} \cdot DE_{bk} \cdot S_b \cdot CC_b \quad (8)$$

$$DC = \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} (x1_{bkjl} + q_{bjl} - q1_{bj}) \cdot \theta_b \cdot DIC_b \quad (9)$$

$$REV = \sum_{b \in B} \sum_{j \in J} q1_{bj} \cdot SP_{bj} \quad (10)$$

The second objective function is to maximize the coverage of collected batteries by opened collection centres or hybrid facilities as represented in Eq. (11). Formulation of this goal is motivated based on the well known “maximal coverage problem” in the literature. The main aim of the maximal covering problem is locating a fixed numbers of facilities within the acceptable distance while maximizing the amount of demand covered. As mentioned, maximal covering problem considers the resources available such as financial resources, fixed investments etc. (in terms of the number of facilities we are able to locate) and determines the maximum demand coverage possible. Maximal covering location problem (MCLP) is defined by Davari et al. [55] as investigating the location of a number of facilities on a network in order to maximize the covered population. For covering a population, at least one facility must be opened within a pre-defined distance of it.

$$\text{Max } Z_2 = \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} DE_{bk} \cdot S_b \cdot y1_{kj} \quad (\text{Goal}_2) \quad (11)$$

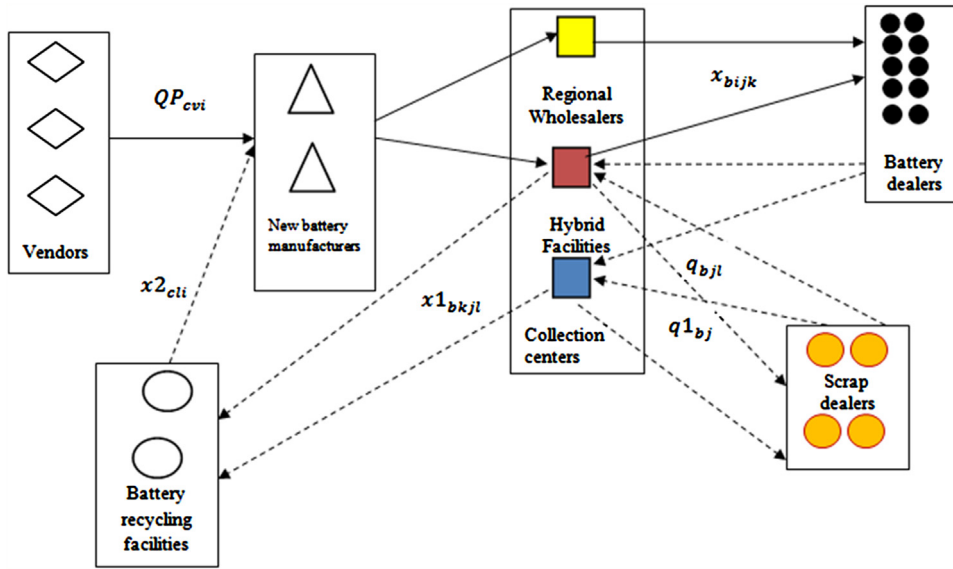


Fig. 2. Structure of the lead/acid battery CLSC network with relational decision variables.

The third objective function is to maximize the total volume flexibility which consists of manufacturing or plant volume flexibility (MVF), distribution volume flexibility (DVF), recycling volume flexibility (RVF) and collection volume flexibility (CVF) as represented in Eqs. (12)–(16). Plant or manufacturing volume flexibility is measured as the difference between plant capacity and plant capacity utilization [8]. Similarly, recycling volume flexibility can be calculated as the difference between recycling facility's capacity and the capacity utilization of this facility. In addition, distribution volume flexibility can be calculated as the difference between the available throughput of the regional wholesalers' or hybrid facilities' and demand requirements of the dealers or retailers. On the other hand, collection volume flexibility is measured as the difference between the collection capacities of opened collection centres and hybrid facilities and the return coverage with purchased scrap batteries by these facilities.

$$\text{Max } Z_3 = W1 \cdot MVF + W2 \cdot DVF + W3 \cdot RVF + W4 \cdot CVF \quad (\text{Goal}_3) \quad (12)$$

$$MVF = \sum_{i \in I} \left(\sum_{b \in B} \text{Prcap}_{bi} - \sum_{b \in B} Q_{bi} \right) \quad (13)$$

$$DVF = \sum_{j \in J} \left(\sum_{b \in B} \text{cap}_{bj}^f \cdot w_j + \text{hcap}_{bj}^f \cdot h_j - \sum_{b \in B} \sum_{k \in K} y_{jk} DE_{bk} \right) \quad (14)$$

$$RVF = \sum_{l \in L} \left(\sum_{b \in B} \frac{\text{REcap}_{bl}}{W_b \cdot \eta} - \sum_{b \in B} \frac{\text{RE}_{bl}}{W_b} \right) \quad (15)$$

$$CVF = \sum_{j \in J} \left(\sum_{b \in B} \text{cap}_{bj}^r \cdot c_j + \text{hcap}_{bj}^r \cdot h_j - \sum_{b \in B} \sum_{k \in K} y1_{kj} \cdot DE_{bk} \cdot S_b - \sum_{b \in B} \sum_{l \in L} q_{bjl} \right) \quad (16)$$

These goals should be satisfied simultaneously and an efficient compromise solution should be generated by the decision makers in the framework of fuzzy aspiration levels. Where the symbols $\lesssim$ and $\gtrsim$ fuzzified version of $\leq$ and $\geq$ and refers to the fuzzification

of the aspiration levels of the decision makers. Constraints are expressed by Eqs. (17)–(41).

$$\sum_{j \in J} c_j + h_j \leq N \quad (17)$$

$$y1_{kj} \leq a_{jk} \cdot (c_j + h_j) \quad \forall j, \forall k \quad (18)$$

$$\sum_{k \in K} y_{jk} \leq M \cdot (h_j + w_j) \quad \forall j \quad (19)$$

$$\sum_{j \in J} y1_{kj} \leq 1 \quad \forall k \quad (20)$$

$$\sum_{j \in J} y_{jk} = 1 \quad \forall k \quad (21)$$

$$\sum_{k \in K} y_{jk} \cdot DE_{bk} \leq \text{cap}_{bj}^f \cdot w_j + \text{hcap}_{bj}^f \cdot h_j \quad \forall b, \forall j \quad (22)$$

$$\sum_{i \in I} x_{bijk} = DE_{bk} \cdot y_{ij} \quad \forall b, \forall k, \forall j \quad (23)$$

$$\sum_{k \in K} y1_{kj} \cdot DE_{bk} \cdot S_b + \sum_{l \in L} q_{bjl} - q1_{bj} \leq \text{cap}_{bj}^r \cdot c_j + \text{hcap}_{bj}^r \cdot h_j \quad \forall b, \forall j \quad (24)$$

$$\sum_{l \in L} x1_{bkjl} = y1_{kj} \cdot [DE_{bk} \cdot S_b] \quad \forall b, \forall k, \forall j \quad (25)$$

$$w_j + c_j + h_j \leq 1 \quad \forall j \quad (26)$$

$$\sum_{j \in J} \sum_{k \in K} x_{bijk} \leq Q_{bi} \quad \forall b, \forall i \quad (27)$$

$$Q_{bi} \leq \text{Prcap}_{bi} \quad \forall b, \forall i \quad (28)$$

$$\left\{ \sum_{k \in K} \sum_{j \in J} x1_{bkjl} + \sum_{j \in J} q_{bjl} - \sum_{j \in J} q1_{bj} \right\} \cdot (1 - \theta_b) \cdot W_b = \text{RE}_{bl} \quad \forall b, \forall l \quad (29)$$

$$\sum_{i \in I} x_{2cli} = \sum_{b \in B} RE_{bl} \cdot \gamma_b \cdot \varepsilon_{cb} \quad \forall c, \forall l \quad (30)$$

$$\sum_{l \in L} q_{bjl} \leq M \cdot y_{bj} \quad \forall b, \forall j \quad (31)$$

$$q_{1bj} \leq M \cdot y_{1bj} \quad \forall b, \forall j \quad (32)$$

$$y_{bj} + y_{1bj} \leq 1 \quad \forall b, \forall j \quad (33)$$

$$d_{2jk} \cdot y_{jk} \leq DMAX \quad \forall j, \forall k \quad (34)$$

$$d_{2jk} \cdot y_{1kj} \leq D1MAX \quad \forall j, \forall k \quad (35)$$

$$\sum_{v \in V} QP_{cvi} + \sum_{l \in L} x_{2cli} = \sum_{b \in B} Q_{bi} \cdot \rho_{cb} \in \forall c, \forall i \quad (36)$$

$$RE_{bl} \leq REcap_{bl} \cdot \eta \in \forall b, \forall l \quad (37)$$

$$x_{1bkjl} + q_{bjl} \leq M \cdot \eta \in \forall b, \forall k, \forall j, \forall l \quad (38)$$

$$\sum_{i \in I} QP_{cvi} \leq Vcap_{cv} \quad \forall c, \forall v \quad (39)$$

$$w_j, c_j h_j, \eta, y_{jk}, y_{1kj}, y_{bj}, y_{1bj} \in (0, 1) \quad (40)$$

$$Q_{bi}, x_{bijk}, x_{1bkjl}, q_{bjl}, q_{1bj} \geq 0 \text{ and integer} \quad (41)$$

All other variables are continuous.

Constraint (17) limits the number of collection centres or hybrid facilities to be opened for spent battery returns. Constraint (18) determines which battery returns are covered within the acceptable service distance. Service means collection of used batteries from the retailers/dealers. If no collection centre or hybrid facility is located, the right hand side of that constraint will be zero and forces the y_{1kj} equal to zero. According to the constraint (19) if a regional wholesaler or hybrid facility is opened, it may serve to any dealer or retailer. In other words, there may be an outgoing flow (distribution operation) from this depot to the dealers. Constraint (20) assures that a battery dealer may be assigned to at most a single collection centre or hybrid facility for spent battery returns. Since these assignments may be impossible because of the logic of maximal covering problem, ≤ 1 is used in that constraint set. Constraint (21) assures that a battery dealer is assigned to a single regional wholesaler or hybrid facility for forward flow of newly produced batteries. In other words, demands of the battery dealers must be satisfied by a single regional wholesaler or hybrid facility. Constraint (22) limits the number of newly produced batteries shipped through the regional wholesaler or hybrid facility to its capacity of performing forward flows. Constraint (23) maintains that the demands of battery dealers' for newly produced batteries must be satisfied. Constraint (24) restricts the number of returned batteries transferred through a collection centre or hybrid facility to its capacity of performing reverse flows. Constraint (25) ensures that volume of returned batteries from a given dealer or retailer is the fraction of total demand of that dealer or retailer. Since the multiplication of demands of the battery dealers by return fractions may produce non-integer values for the related decision variable (x_{1bkjl}), rounding function was used in order to return the nearest integer value. Constraint (26) ensures that at most one type of facility (regional wholesaler, collection centre or hybrid facility) can be opened at the potential depot locations. Constraint (27) guarantees that the outgoing flows from a new battery manufacturer cannot exceed the production quantity at that manufacturer. Constraint (28) ensures that the production quantity of each battery type must not get over the production capacity of the new battery manufacturers. According to constraint (29), one can calculate the quantity of used batteries in weight that are recyclable. Constraint (30) is the conservation of flow constraint for the licensed recycling facilities.

Table 3

Data ranges used in the illustrative example.

Parameters	Range of values
Demand forecasts of battery dealers (units)	Uniform distribution (500, 2500)
Unit production cost (\$/unit)	25–65
Unit transportation cost for newly produced batteries (\$/km unit)	0.001–0.003
Unit transportation cost for used batteries (\$/km unit)	0.002–0.004
Unit transportation cost for materials/components (\$/kg unit)	0.008–0.015
Recycling cost (\$/kg.)	0.47–1.0
Unit collection cost (\$/unit)	2–5
Unit disposal cost (\$/unit)	1–3
Unit purchasing cost of used batteries from scrap dealers (\$/unit)	5–14
Unit selling price of used batteries to scrap dealers (\$/unit)	5–14
Unit purchasing cost for components from the vendors (\$/kg)	0.7–4
Maximum number of opened collection centres and hybrid facilities	5
Fixed cost of opening regional wholesaler (\$)	150,000–230,000
Fixed cost of opening collection centres (\$)	90,000–150,000
Fixed cost of opening hybrid facilities (\$)	360,000–522,000
Fixed cost of opening licensed recycling facilities (\$)	400,000–600,000
Production capacity of battery manufacturers (units)	28,000–56,000
Capacity of regional wholesalers (units)	7000–14,000
Capacity of collection centres (units)	10,000–20,000
Capacity of hybrid facilities for forward flows (units)	5250–10,500
Capacity of hybrid facilities for reverse flows (units)	7000–14,000
Capacity of licensed recycling facilities (kg)	750,000–4,550,000
Capacity of vendors (units)	50,000–90,000
Return fraction	70–90%
Disposal rate	5–10%
Recycling rate	70–80%
Weight of used batteries (kg/unit)	15–35
Contribution percentages of materials/components	10–55%
Distances (km)	0–1650
Max. acceptable distances (km)	400–500
Weight factors for capacity utilizations	25%

Constraint (31) and (32) provide that the variables related to quantities must take value in the case of used battery purchasing from the scrap dealers or sales of used batteries to the scrap dealers. Constraint (33) ensures that purchasing and selling operations for the same type of scrap batteries cannot be actualized simultaneously (in that single time period). At most one of these variables can take a value for each battery type and each collection centre or hybrid facility. Constraint (34) and (35) assure that each regional wholesaler, collection centre or hybrid facility should be located within acceptable proximity of battery dealers. Constraint (36) is balance equation for the components that are used in the new battery production. Constraint (37) and (39) are capacity constraints for the licensed recycling facilities and vendors, respectively. Constraint (38) makes sure that if a licensed recycling facility is opened at the candidate location, there may be incoming flows of used batteries from the collection centres, hybrid facilities or scrap dealers to this recycling facility. Constraint (40) represents the binary variables such as opening decisions for the facilities (regional wholesalers, collection centres, hybrid facilities and licensed recycling facilities); assignment decisions for allocating battery dealers to the regional wholesalers, collection centres and hybrid facilities and decisions regarding scrap battery purchasing or sales. Finally, constraint (41) enforces the non-negativity restrictions. Production (Q_{bi}) and transportation variables (x_{bijk} and x_{1bkjl}); also variables correspond to

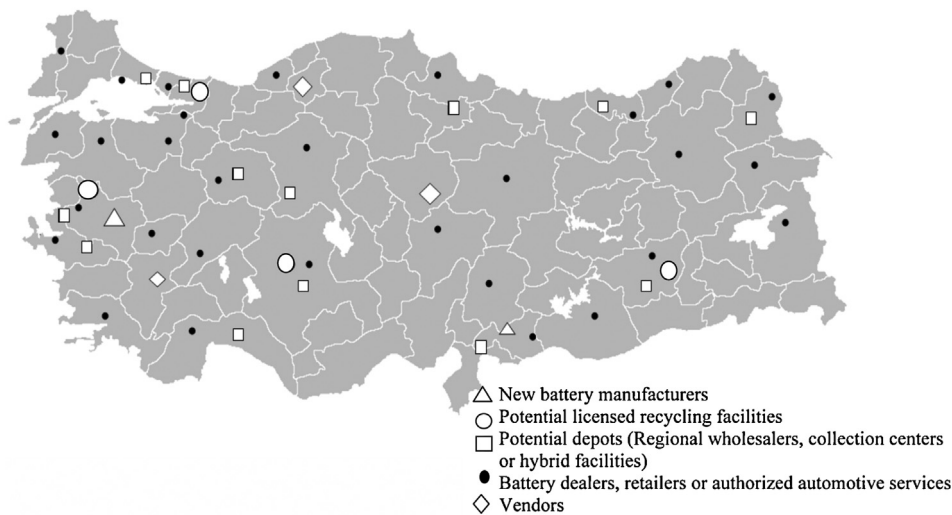


Fig. 3. Configuration of computational case study.

spent battery purchases and sales (q_{bjl} and q_{1bj}) should take integer values since they are subject to disjunctive constraints [56].

4. Model implementation

4.1. Computational case study and data description

In order to observe the performance of the proposed FMOLP model, an illustrative example is generated based on inspiration from a lead/acid battery CLSC in Turkey. Configuration of the computational case study is shown in Fig. 3. There are three types of batteries, three types of components, two new battery manufacturers, three vendors to supply components/raw materials, thirty dealers or retailers with uniformly distributed yearly demands, thirteen potential sites for collection, distribution or both activities as hybrid facilities and four alternatives for licensed recycling facilities in the case study. Actually, uniform distribution is used since the demands are considered in an aggregated manner.

The proposed FMOLP model for network design problem of the CLSC aims obtaining an optimal network structure which includes best locations of regional wholesalers, collection centres, hybrid facilities and licensed recycling facilities. Parameter intervals used in the computational case study are given in Table 3. When the model is run with these data through a mixed integer programming solver ILOG OPL Studio version 6.3 including CPLEX 12.1.0 product on an Intel Core i7 2 GHz IBM PC for each objective separately, the optimization results and independent objective function values are obtained as shown in Table 4. Moreover, corresponding optimal

network structures for each objective are represented in Figs. 4–6. According to the Fig. 4, forward and reverse flows are performed between the nodes which are closest to each other in order to minimize the transportation costs. It is also seen that all of the collection centres purchased additional spent batteries from the scrap dealers for obtaining cost advantage. As it is seen from Fig. 4, one of the new battery manufacturers acquired all of the component requirements from the recycling. However, the other manufacturer acquired components from both purchasing and recycling.

On the other hand, it is obviously seen that network configuration has spread to farther distances (as shown in Fig. 5) in order to collect spent batteries as much as possible. As well as purchasing spent batteries from the scrap dealers, spent batteries are sold to scrap dealers by the one of the collection centres for different spent battery types.

There are component flows from the all opened licensed recycling facilities to the all new battery manufacturers. Only spent battery purchasing is available from the scrap dealers similar with the first objective according to Fig. 5. In addition, since the reverse flow capacities of the hybrid facilities are much larger than the collection centres, only one collection centre and four hybrid facilities are opened in case of considering third objective independently.

5. FGP-DIP for the strategic planning of a lead/acid battery CLSC

Multi-objective, multi-echelon and multi-product linear programming model for the network design problem of a lead/acid

Table 4
Optimization results of the deterministic model solution considering objective functions separately.

	Total cost objective-1	Total coverage objective-2	Total flexibility objective-3
Total number of variables	8179	8179	8179
Total number of integer variables	7221	7221	7221
Total number of binary variables	901	901	901
Total number of constraints	8537	8537	8537
Total number of iterations	46,098	4260	32,285
Total cost of the CLSC	\$12,018,344.74 (optimal IP solution)	\$15,850,000	\$16,535,000
Total maximal coverage	84,207 units	101,157.05 units (optimal IP solution)	65,181 units
Total volume flexibility	81,453 units	293,080 units	304,359.99 (optimal IP solution)
CPU time (s)	10.54 s	2.30 s	3.79 s
Number of opened regional wholesalers	6	8	8
Number of opened collection centres	4	3	1
Number of opened hybrid facilities	None	2	4
Number of opened licensed recycling facilities	1	4	4

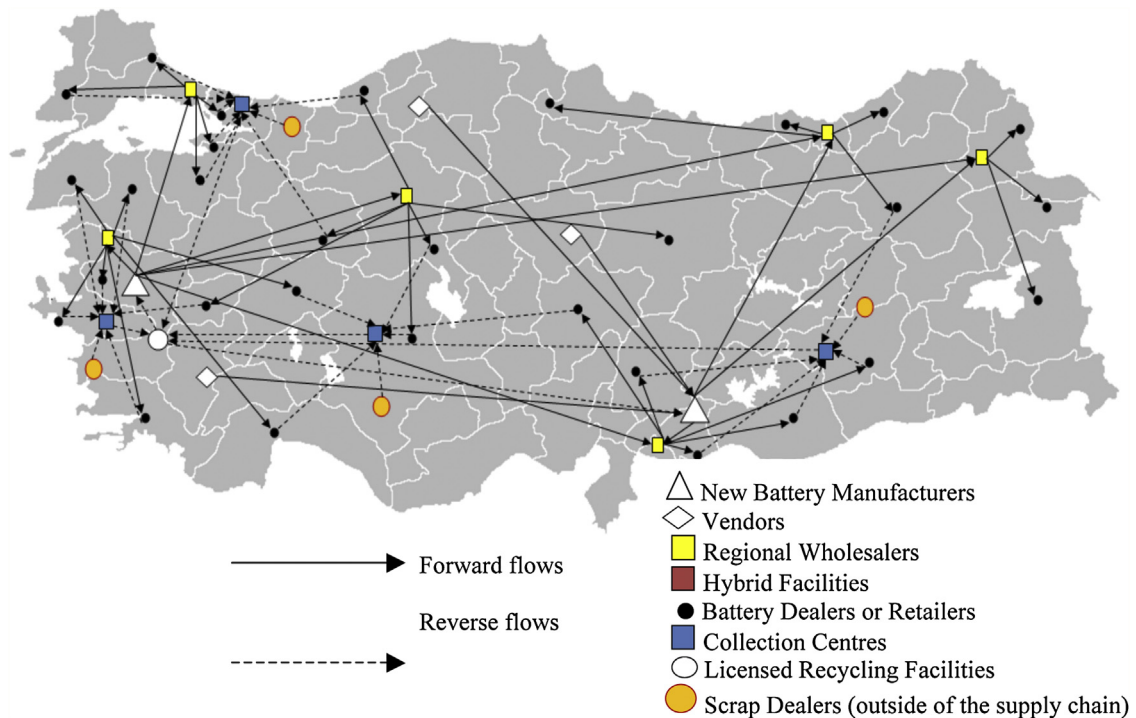


Fig. 4. Optimal forward and reverse network structure considering only the first goal.

battery CLSC can be converted to FMOLP model by displaying membership functions to represent the fuzzy goals of decision makers (DMs). In this study, it is assumed that all of the objectives defined earlier have different importance and priorities. Moreover, desirable achievement degree for each fuzzy goal is determined by three DMs who are the supply chain director, financial advisor and marketing & recycling manager. According to the board chairman, these DMs have different importance/weights while evaluating the relative importance of the fuzzy goals. Furthermore, index of optimism which reflects the decision maker's risk taking attitude may differ from one DM to another [57]. For this reason, it is assumed that these DMs have different indexes of optimism such as optimistic, pessimistic and moderate which represent the characters or

optimistic attitude of the DMs which is essential for the decision making process.

5.1. Construction of the membership functions

The solutions which are obtained after solving the deterministic models for each objective function separately (see Table 4) are used as benchmarks to construct membership functions by the DMs. Membership functions of the fuzzy goals are defined on the interval [0,1] and if the membership function value of k th goal is equal to 1, we can say that decision maker is fully satisfied. Otherwise, the membership function takes a value between 0 and 1. In the literature and practice, linear type of membership functions

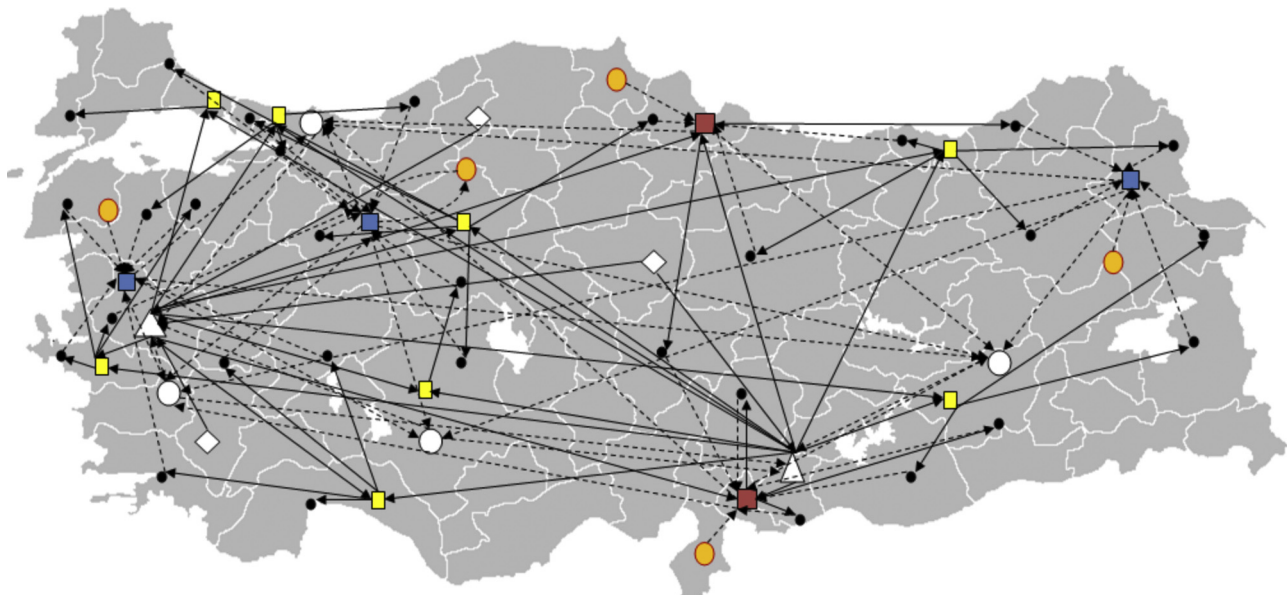


Fig. 5. Optimal forward and reverse network structure considering only the second goal.

Table 5
The payoff table.

	$Z_1(X)$	$Z_2(X)$		$Z_k(X)$
$X^{(1)}$	Z_{11}	Z_{12}		Z_{1k}
$X^{(2)}$	Z_{21}	Z_{22}		Z_{2k}
...	...	...	...	...
$X^{(k)}$	Z_{k1}	Z_{k2}		Z_{kk}

Table 6
Corresponding payoff table.

Objectives	Total CLSC cost	Total coverage	Total flexibility
Total CLSC cost	\$12,018,344.74	84,207 units	81,453 units
Total coverage	\$15,850,000	101,157.05	293,080 units
Total flexibility	\$16,535,000	65,181 units	304,359.99 units

such as triangular or trapezoid are generally preferred since they include less computation [1]. In order to determine the membership function of each fuzzy objective, FGP requires determination of the aspiration levels and max-min limits of these goals. Generally, decision makers estimate the lower and upper limits based on their knowledge and experience. These max-min limits were estimated by [38,54] by using the payoff table (see Table 5) and guaranteed the feasibility of each fuzzy goal in the solution phase. Here, $Z_k(X)$ is the k th objective function and $X^{(k)}$ is its optimal solution. The payoff matrix can be derived by solving the k -single objective problem with $X^{(k)}$ ($k = 1, 2, \dots, K$) solution vectors (in other words, putting the optimal value to other objective functions).

The main diagonal in the matrix which is presented in Table 5 denotes the individual best solutions for each objective. Then, the limits can be determined for minimization and maximization problems as follows:

$$Z_k^l = Z_{kk} \text{ and } Z_k^u = \max(Z_{1k}, Z_{2k}, \dots, Z_{kk}) \quad (42)$$

$$Z_k^u = Z_{kk} \text{ and } Z_k^l = \min(Z_{1k}, Z_{2k}, \dots, Z_{kk}) \quad (43)$$

where Z_k^l and Z_k^u mean lower and upper bounds for the k th objective function. By using the results in Table 4, payoff table of the current problem can be derived as in Table 6. Then, lower and upper bounds can be determined as in Table 7 in order to be used in the

Table 7
Limits for the objectives.

Objectives	Lower bound	Upper bound
Total CLSC cost	\$12,018,344.74	\$16,535,000
Total coverage	65,181 units	101,157.05
Total flexibility	81,453 units	304,359.99 units

construction of membership functions for satisfaction levels of the goals.

To quantify the fuzzy aspiration levels of the objectives, linear and continuous membership functions are found appropriate. The membership function for each fuzzy goal and regarding analytical definitions are shown as in the following Figs. 7–9 based on [59].

5.2. Determination of desirable achievement degrees using linguistic evaluations in a group decision making environment

The determination of a desirable achievement degree for a goal is a difficult and troublesome task for the DMs in a fuzzy environment. For selecting the desirable achievement degrees imprecisely, a recommended method is to use linguistic terms such as ‘important’, ‘somewhat important’ and ‘very important’ and so on, to verbally define the importance of each fuzzy goal [6]. The linguistic term is a variable whose values are words or phrase in natural or artificial language [50]. A fuzzy linguistic variable is often characterized by fuzzy numbers [60]. In order to determine the desirable achievement degrees of the objectives and to deal with the imprecise or vague nature of linguistic assessment we employed Liou and Wang’s approach [49] for ranking fuzzy numbers in group decision making environment where the weights/importance and index of optimism of each group member are different. Before applying this method, $L = \{VLI, LI, SLI, M, SHI, HI, VHI\}$ is defined as a set of linguistic values about the importance of different goals where VLI = very low important, LI = low important, SLI = somewhat low important, M = medium, SHI = somewhat high important, HI = high important, VHI = very high important.

Fig. 10 shows the membership functions for linguistic values about the importance of different objectives and DMs. Where $\mu_L(\alpha)$ represents the membership functions of each linguistic values,

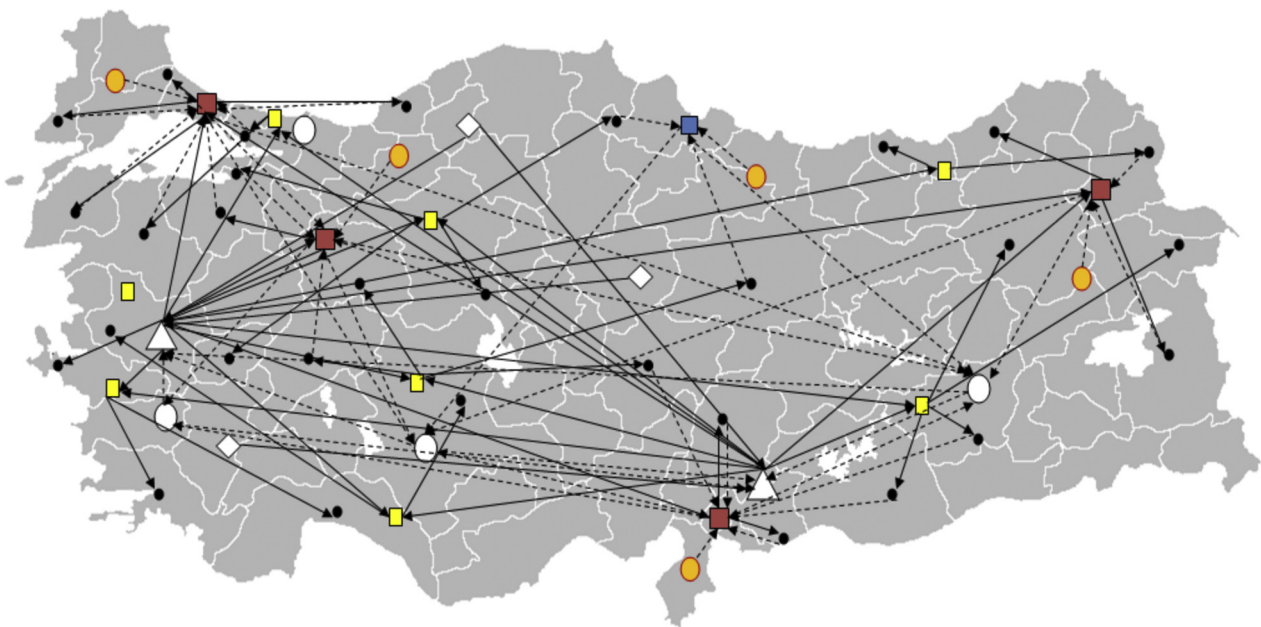


Fig. 6. Optimal forward and reverse network structure considering only the third goal.

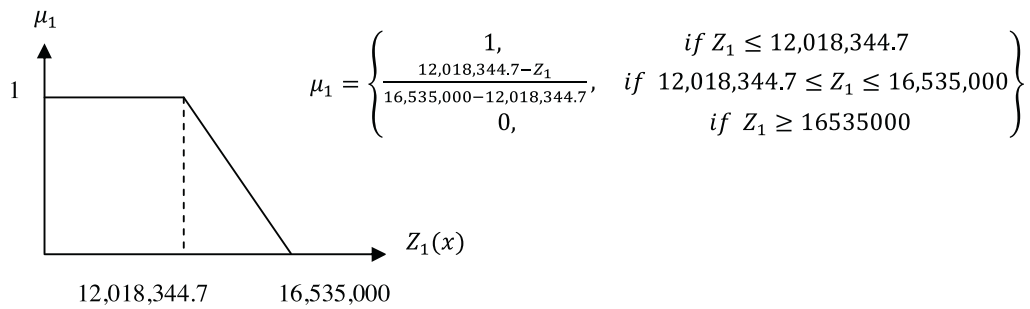


Fig. 7. Membership function of fuzzy minimum Z_1 (Minimize the total cost of the CLSC).

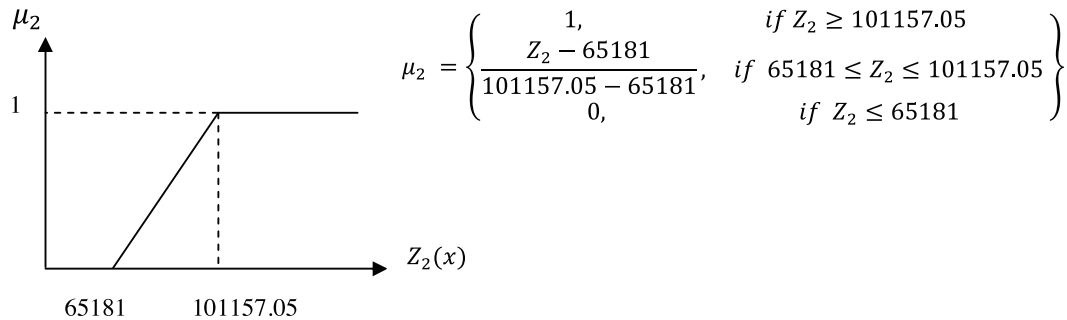


Fig. 8. Membership function of fuzzy maximum Z_2 (Maximize the total coverage of the collected batteries).

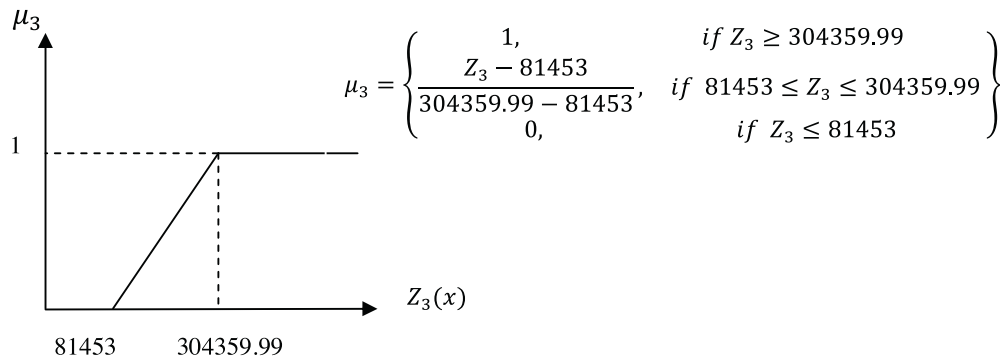


Fig. 9. Membership function of fuzzy maximum Z_3 (Maximize the total volume flexibility).

Table 8
Linguistic variables for the importance/weight of different goals and DMs [50].

Linguistic variables	Triangular fuzzy numbers
Very low important (VLI)	(0,0,%10)
Low important (LI)	(%5,%15,%25)
Somewhat low important (SLI)	(%20,%32.5,%45)
Medium (M)	(%40,%50,%60)
Somewhat high important (SHI)	(%55,%67.5,%80)
High important (HI)	(%75,%85,%95)
Very high important (VHI)	(%90,%100,%100)

$\mu_L(\alpha) \in [0, 1]$ and α shows the variable taking an achievement degree in the interval of $[\alpha_{min}, \alpha_{max}]$, $0 \leq \alpha_{min} \leq \alpha_{max} \leq 1$.

These linguistic values about the importance of different goals and DMs are characterized by triangular fuzzy numbers as shown in Table 8.

In the approach of [49], where; $\alpha \in [0, 1]$ and represents the index of optimism in order to reflect the decision maker's

optimistic attitude, the total integral value $I_T^\alpha(\tilde{A})$ of the triangular fuzzy number $\tilde{A} = (a, b, c)$ can be calculated as follows [51,58,61]:

Let $\tilde{A}$ is a triangular fuzzy number with membership function $\mu_{\tilde{A}}(x)$. Also, $\mu_{\tilde{A}}^L(x)$ and $\mu_{\tilde{A}}^R(x)$ are left and right membership functions of the triangular fuzzy number $\tilde{A}$. Then, the left and right integral value of $\tilde{A}$ can be defined as follows [62]:

$$I_L(\tilde{A}) = \int_0^1 g_{\tilde{A}}^L(y) dy \text{ and } I_R(\tilde{A}) = \int_0^1 g_{\tilde{A}}^R(y) dy \quad (47)$$

where $g_{\tilde{A}}^L(y)$ and $g_{\tilde{A}}^R(y)$ represent the inverse functions of $\mu_{\tilde{A}}^L(x)$ and $\mu_{\tilde{A}}^R(x)$, respectively. These inverse functions can be formulated as in Eq. (48).

$$g_{\tilde{A}}^L(y) = a + (b - a)y \text{ and } g_{\tilde{A}}^R(y) = c + (b - c)y \quad (48)$$

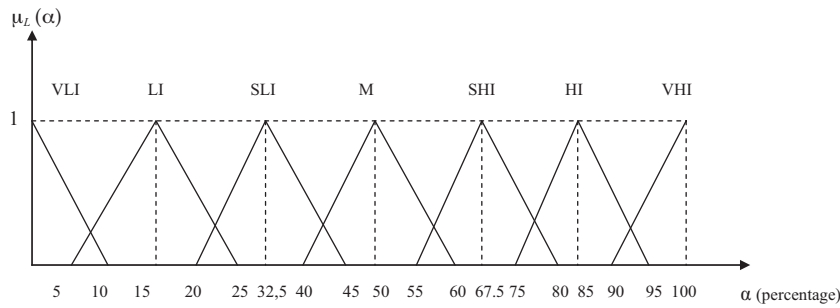


Fig. 10. Membership functions for linguistic values [51].

Table 9
Pair-wise comparison for the weights of the decision makers in the group decision making.

	DM 1	DM 2	DM 3
DM 1	M	HI	SHI
DM 2	LI	M	SLI
DM 3	SLI	SHI	M

Table 10
Fuzzy evaluation matrix for the DMs.

	DM 1	DM 2	DM 3
DM 1	(0.4,0.5,0.6)	(0.75,0.85,0.95)	(0.55,0.675,0.8)
DM 2	(0.05,0.15,0.25)	(0.4,0.5,0.6)	(0.2,0.325,0.45)
DM 3	(0.2,0.325,0.45)	(0.55,0.675,0.8)	(0.4,0.5,0.6)

where $y \in [0, 1]$. Then, total integral value of $\tilde{A}$ with index of optimism $\alpha \in [0, 1]$, $I_T^\alpha(\tilde{A})$ can be calculated as follows:

$$I_T^\alpha(\tilde{A}) = \alpha I_R(\tilde{A}) + (1 - \alpha)I_L(\tilde{A}) = \frac{1}{2} [\alpha(b + c) + (1 - \alpha)(a + b)]$$

$$= \frac{1}{2} [\alpha c + b + (1 - \alpha)a] \quad (49)$$

When $\alpha = 0$, total integral value represents a pessimistic decision maker and it is calculated through Eq. (50).

$$I_T^0(\tilde{A}) = \frac{1}{2} [b + a] \quad (50)$$

When $\alpha = 0.5$, total integral value represents a moderate decision maker and it is calculated through Eq. (51).

$$I_T^{0.5}(\tilde{A}) = \frac{1}{2} [0.5c + b + 0.5a] \quad (51)$$

When $\alpha = 1$, total integral value represents an optimistic decision maker and it is calculated through Eq. (52).

$$I_T^1(\tilde{A}) = \frac{1}{2} [c + b] \quad (52)$$

We can use $I_T^\alpha(\tilde{A}) = \alpha_{ik}$ as the desired achievement degree of the k th fuzzy goal for i th DM. In this study, the computational procedure of the Chang's [60] extent fuzzy analytic hierarchy process (AHP) is used to determine the weights of the group members. A pair-wise matrix which is determined by the board chairman for assigning the weights of each group member is given in the following Table 9. Since "Medium" with (0.40, 0.50, 0.60) triangular fuzzy number refers to the equally important, "M" is used as a linguistic term while comparing the same decision makers [63].

Then the fuzzy evaluation matrix in Table 10 which composes of triangular fuzzy numbers can be derived by using Table 8.

The computational procedure of the Chang's [60] extent fuzzy AHP is described as follows:

Step 1: The value of the fuzzy synthetic extent with respect to the i -th object is defined by:

$$S_i = \sum_j^m M_{g_i}^j \otimes \left[\sum_i^n \sum_j^m M_{g_i}^j \right]^{-1} \quad (53)$$

Where all the $M_{g_i}^j$ ($j = 1, 2, \dots, m$) are triangular fuzzy numbers.

Step 2: As $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two triangular fuzzy numbers, the degree of possibility of $M_1 \geq M_2$ is defined by:

$$V(M_2 \geq M_1) = \begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0, & \text{if } l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases} \quad (54)$$

Step 3: To compare M_1 and M_2 , we need both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$. The degree possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i ($i = 1, 2, \dots, k$) can be defined by:

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and } \dots \text{ and } (M \geq M_k)] = \min V(M \geq M_i), i = 1, 2, \dots, k \quad (55)$$

Assume that $d'(A_i) = \min V(S_i \geq S_k)$ for $k = 1, 2, \dots, n; k \neq i$ then the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \quad (56)$$

Where A_i ($i = 1, 2, \dots, n$) are n elements.

Step 4: Via normalization, the normalized weight vectors are:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \quad (57)$$

Where, W is a non-fuzzy number.

According to the Fig. 11, where d is the ordinate of the highest intersection point d between μ_{M_1} and μ_{M_2} .

$$V(M_1 \geq M_2) = 1 \text{ if } m_1 \geq m_2,$$

$$V(M_1 \geq M_2) = \text{hgt}(M_1 \cap M_2) = \mu_{M_1} \quad (58)$$

The ordinate of the highest intersection point d is given by Eq. (59):

$$V(M_2 \geq M_1) = \text{hgt}(M_1 \cap M_2) = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \quad (59)$$

This procedure is utilized for assigning the weights of DMs in the decision making process. The value of the fuzzy synthetic extent is calculated by Eq. (53) as follows:

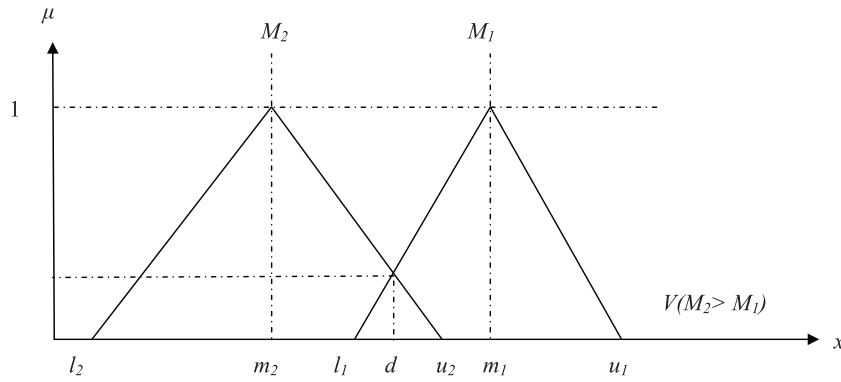


Fig. 11. The intersection between M_1 and M_2 [64].

For instance, this can be calculated for decision maker-1 as follows:

$$S_{Z_1} = \sum_{j=1}^3 M_{g_1}^j \otimes \left[\sum_{i=1}^3 \sum_{j=1}^3 M_{g_i}^j \right]^{-1}$$

By performing fuzzy addition operation:

$$\begin{aligned} \sum_{j=1}^3 M_{g_1}^j &= (0.4, 0.5, 0.6) \oplus (0.75, 0.85, 0.95) \oplus (0.55, 0.675, 0.8) \\ &= (1.7, 2.025, 2.35) \end{aligned}$$

By performing fuzzy addition operation and inverse of a fuzzy number [65]:

$$\begin{aligned} \sum_{i=1}^3 \sum_{j=1}^3 M_{g_i}^j &= (0.4, 0.5, 0.6) \oplus (0.75, 0.85, 0.95) \oplus \dots \\ &\oplus (0.55, 0.675, 0.8) \oplus (0.4, 0.5, 0.6) = (3.5, 4.5, 5.5) \end{aligned}$$

$$\left[\sum_{i=1}^3 \sum_{j=1}^3 M_{g_i}^j \right]^{-1} = \left(\frac{1}{5.5}, \frac{1}{4.5}, \frac{1}{3.5} \right)$$

$$S_{Z_1} = (1.7, 2.025, 2.35) \otimes \left(\frac{1}{5.5}, \frac{1}{4.5}, \frac{1}{3.5} \right) = (0.309, 0.45, 0.671)$$

$$\begin{aligned} S_{Z_{12}} &= (0.65, 0.975, 1.3) \otimes \left(\frac{1}{5.5}, \frac{1}{4.5}, \frac{1}{3.5} \right) \\ &= (0.118, 0.216, 0.371) \end{aligned}$$

$$S_{Z_3} = (1.15, 1.5, 1.85) \otimes \left(\frac{1}{5.5}, \frac{1}{4.5}, \frac{1}{3.5} \right) = (0.209, 0.333, 0.529)$$

These fuzzy values should be compared.

$$\begin{aligned} V(Z_1 \geq S_{Z_2}) &= 1, & V(S_{Z_1} \geq S_{Z_3}) &= 1 \\ V(S_{Z_2} \geq S_{Z_1}) &= 0.209, & V(S_{Z_2} \geq S_{Z_3}) &= 0.581 \\ V(S_{Z_3} \geq S_{Z_1}) &= 0.653, & V(S_{Z_3} \geq S_{Z_2}) &= 1 \end{aligned}$$

Then, priority weights are calculated as follows:

$$\begin{aligned} d'(Z_1) &= \min(1, 1) = 1 \\ d'(Z_2) &= \min(0.209, 0.581) = 0.209 \\ d'(Z_3) &= \min(0.653, 1) = 0.653 \end{aligned}$$

Table 11
Evaluations of the relative importance of the objectives by DMs.

	Supply Chain Director (Moderate)	Financial Advisor (Optimistic)	Marketing & Recycling Manager (Pessimistic)
Total CLSC costs	HI	VHI	HI
Total coverage	HI	SHI	SHI
Total volume flexibility	M	SHI	SLI

Priority weights form $W' = (1, 0.209, 0.653)$ vector. After normalization of these values, normalized weight vectors are calculated as $W = (0.54, 0.11, 0.35)$. Therefore, weights of the three decision makers in group decision making process are obtained based on fuzzy-AHP method. In this study, importance of the objectives is evaluated by the three decision makers with different index of optimism as shown in Table 11.

Obtaining desirable achievement degree for each fuzzy goal is achieved in five steps in this paper:

1. Determine the weights/importance of each group member
2. Specify the index of optimism of each group member
3. Obtain the linguistic assessment of each fuzzy goal from the DMs
4. Calculate the individual desirable achievement degree of each goal for each DM as in Table 12 based on the related total integral value $I_T^\alpha(\tilde{A})$ by using either Eqs. (50), (51) or (52) while taking into account the optimism index of each DM. For instance, individual desirable achievement degree of the first objective for the DM-1 which has a moderate optimism character (α_{11}) can be calculated as follows:

$$\begin{aligned} \alpha_{11} &= I_T^{0.5}(\tilde{A}) = \frac{1}{2} [0.5c + b + 0.5a] = I_T^{0.5}(0.75, 0.85, 0.95) \\ &= \frac{1}{2} [0.5 * 0.95 + 0.85 + 0.5 * 0.75] \end{aligned}$$

5. Finally, calculate the overall priority of each fuzzy goal by using Eq. (60) based on the weighted geometric mean.

$$\bar{\alpha}_k = \left(\prod_{i=1}^n \alpha_{ik}^{w_i} \right)^{1/\sum_{i=1}^n w_i} \quad (60)$$

Where $\bar{\alpha}_k$ is overall priority of the k th fuzzy goal, α_{ik} is the individual desirable achievement degree of i th DM for k th fuzzy goal and w_i is weight of the i th DM. Overall priorities are obtained by using the above procedure as shown in the Table 12.

Therefore, desirable achievement degrees are determined in a group decision making environment where the decision makers

Table 12
Overall priorities for determination of desirable achievement degrees.

	DM 1 (Moderate-0.54)	DM 2 (Optimistic-0.11)	DM 3 (Pessimistic-0.35)	Overall Priority $\bar{\alpha}_k$
Total CLSC cost	(0.75,0.85,0.95) $\alpha_{11} = 0.85$	(0.9,1.0,1.0) $\alpha_{21} = 1.0$	(0.75,0.85,0.95) $\alpha_{31} = 0.8$	0.847
Total coverage	(0.75,0.85,0.95) $\alpha_{12} = 0.85$	(0.55,0.675,0.8) $\alpha_{22} = 0.7375$	(0.55,0.675,0.8) $\alpha_{32} = 0.6125$	0.746
Total volume flexibility	(0.4,0.5,0.6) $\alpha_{13} = 0.5$	(0.55,0.675,0.8) $\alpha_{23} = 0.7375$	(0.2,0.325,0.45) $\alpha_{33} = 0.2625$	0.416

have different weights and index of optimism as 0.847, 0.746 and 0.416 based on [49].

5.3. Transformation of FMOLP problem to equivalent crisp model

The proposed FMOLP model is converted to an equivalent LP model as described in [6] with one objective function that maximizes the summation of achievement degrees of the fuzzy goals. In the crisp model, $\mu_k \geq \bar{\alpha}_k$ is added for all k goals to the system constraints. Desirable achievement degrees or overall priorities can be defined as the importance of the fuzzy goals. Therefore, more important goals have higher achievement degrees [6]. Also, the membership functions of the fuzzy objectives μ_{Z_k} are known. The transformation of the fuzzy optimization problem that is proposed earlier in section 3.5 into an equivalent crisp model is as follows:

$$\text{Maximize } f(\mu) = \sum_{k=1}^3 \mu_k = \mu_1 + \mu_2 + \mu_3 \quad (61)$$

Subject to:

$$\begin{aligned} Z_1 = & \sum_{j \in J} f1_j \cdot w_j + \sum_{j \in J} f2_j \cdot c_j + \sum_{j \in J} f3_j \cdot h_j + \sum_{l \in L} f4_l \cdot \eta + \sum_{c \in C} \sum_{v \in V} \sum_{i \in I} QP_{cvi} \cdot PUC_{cvi} + \\ & \sum_{b \in B} \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} x_{bijl} \cdot TC_b \cdot (d1_{ij} + d2_{jk}) + \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} x1_{bkjl} \cdot TC1_b \cdot (d2_{jk} + d3_{il}) + \\ & \sum_{b \in B} \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} q_{bjl} \cdot TC1_b \cdot d3_{jl} + \sum_{c \in C} \sum_{l \in L} \sum_{i \in I} x2_{cli} \cdot TC_c \cdot d4_{li} + \sum_{b \in B} \sum_{i \in I} Q_{bi} \cdot PRC_b + \\ & \sum_{b \in B} \sum_{j \in J} \sum_{l \in L} q_{bjl} \cdot PC_{bj} - \sum_{b \in B} \sum_{j \in J} q1_{bj} \cdot SP_{bj} + \sum_{b \in B} \sum_{l \in L} RE_{bl} \cdot RC_{bl} + \sum_{b \in B} \sum_{j \in J} \sum_{k \in K} y1_{kj} \cdot DE_{bk} S_b \cdot CC_b + \\ & \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} \sum_{l \in L} (x1_{bkjl} + q_{bjl} - q1_{bj}) \cdot \alpha_b \cdot DIC_b \end{aligned} \quad (62)$$

$$Z_2 = \sum_{b \in B} \sum_{k \in K} \sum_{j \in J} DE_{bk} \cdot S_b \cdot y1_{kj} \quad (63)$$

$$\begin{aligned} Z_3 = & W1 \cdot \sum_{i \in I} \left(\sum_{b \in B} Prcap_{bi} - \sum_{b \in B} Q_{bi} \right) + W2 \cdot \sum_{j \in J} \left(\sum_{b \in B} cap_{bj}^f \cdot w_j + hcap_{bj}^f \cdot h_j - \sum_{b \in B} \sum_{k \in K} y_{jk} \cdot DE_{bk} \right) + \\ & W3 \cdot \sum_{l \in L} \left(\sum_{b \in B} REcap_{bl} / W_b \cdot \eta - \sum_{b \in B} RE_{bl} / W_b \right) + W4 \cdot \sum_{j \in J} \left(\sum_{b \in B} cap_{bj}^r \cdot c_j + hcap_{bj}^r \cdot h_j - \sum_{b \in B} \sum_{k \in K} y1_{kj} \cdot DE_{bk} \cdot S_b - \sum_{b \in B} \sum_{l \in L} q_{bjl} \right) \end{aligned} \quad (64)$$

$$\mu_1 \leq \frac{16,535,000 - Z_1}{4,516,656} \quad (65)$$

$$\mu_2 \leq \frac{Z_2 - 65181}{35976} \quad (66)$$

$$\mu_3 \leq \frac{Z_3 - 81453}{222906} \quad (67)$$

Constraint set from (17)–(41)

$$\mu_1 \geq 0.847 \quad (68)$$

$$\mu_2 \geq 0.746 \quad (69)$$

$$\mu_3 \geq 0.416 \quad (70)$$

$$\mu_1, \mu_2, \mu_3 \leq 1 \quad (71)$$

A simplified flow chart which outlines the solution procedure of the proposed model is shown in Fig. 12.

An infeasibility problem may arise if the achievement degrees are set to very high values in the proposed model. In order to handle this problem, membership functions may be revised according to the decision makers' preferences instead of using payoff table directly to determine the aspiration levels and tolerance values for the objectives. If the problem continues, achievement degree reductions and/or model parameter revisions can also be considered.

5.4. Fuzzy optimization results of the case study

Solution of the equivalent crisp model (by using ILOG OPL Studio version 6.3 modelling language) yields the following optimal network structure and optimal production-recycling plan as presented in Tables 13–15 and Figs. 13 and 14.

According to the results obtained from the efficient compromise solution that is provided with the satisfaction of multiple fuzzy goals, six of the regional wholesalers, none of the hybrid facilities, five of collection centres and three of the licensed recycling facilities should be opened at the candidate or potential locations. Moreover, objective function values for the optimal individual solutions and FMOLP solution are given in Fig. 13.

It can be clearly seen from Fig. 13 that fuzzy compromise solution which considers all objectives simultaneously gives close-by results to the optimal deterministic individual solutions for each objective function. In the fuzzy compromise solution, total revenue obtained from the used battery sales is equal to zero. This

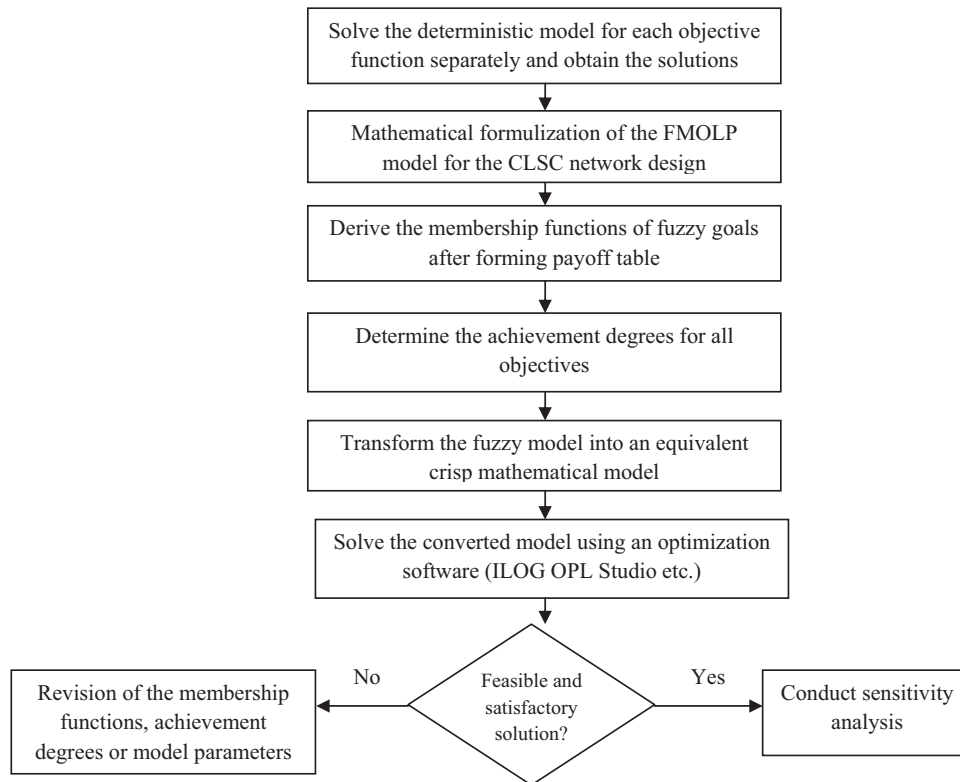


Fig. 12. Flow chart for solution procedure of FGP-DIP for CLSC network design problem.

means no spent battery sales to the scrap dealers are available. Instead of selling of used batteries from the hybrid facilities or collection centres to the scrap dealers, purchasing of them are more advantageous when considering the three objectives simultaneously. Optimal production/recycling quantities of each battery type at each new battery manufacturer and opened recycling facility for both optimal individual solutions and FMOLP solution

are given in Table 14. Furthermore, transportation quantities of recycled materials/components (in kilograms) from the licensed recycling facilities to the new battery manufacturers are also given in Table 15. Therefore, in this fuzzy compromise solution, first new battery manufacturer meets most of its component/material requirements via recycling option since the first potential recycling facility is opened next to it. As it is seen from the Fig. 14, spent bat-

Table 13
Results of the fuzzy optimization.

Total CLSC cost	Total coverage	Total volume flexibility	CPU time	Total number of variables-constraints	Satisfaction degrees μ_1, μ_2, μ_3
\$12,629,000	96,313 units	210,220 units	92.43 s	8183–8547	0.851 0.865 0.577

Table 14
Optimal production-recycling quantities for the optimal individual solutions and FMOLP solution.

		Obj 1	Obj 2	Obj 3	FMOLP
New Battery Manufacturer-1	Battery Type-1	35,000 units	9724 units	35,000	29,425
	Battery Type-2	28,000	7863	28,000	22,248
	Battery Type-3	41,820	41,007	38,695	34,701
New Battery Manufacturer-2	Battery Type-1	8116	33,392	8116	13,691
	Battery Type-2	14,957	35,094	14,957	20,709
	Battery Type-3	0	1979	3125	7119
Licensed recycling facility-1	Battery Type-1	950,620 kg	126,620	319,590	458,720
	Battery Type-2	1,098,000	164,090	0	604,090
	Battery Type-3	1,288,000	0	32.2	1,170,300
Licensed recycling facility-2	Battery Type-1	Unopened	25,015	0	40.5
	Battery Type-2		0	0	41,336
	Battery Type-3		0	1,223,200	0
Licensed recycling facility-3	Battery Type-1	Unopened	334,110	0	Unopened
	Battery Type-2		1,095,700	0	
	Battery Type-3		202,730	32.2	
Licensed recycling facility-4	Battery Type-1	Unopened	529,420	576,050	410,550
	Battery Type-2		0	1,220,200	514,570
	Battery Type-3		910,200	418.6	139,880

Table 15
Amounts of recycled materials (kg.) transported from licensed recycling facilities to manufacturers.

			Obj 1	Obj 2	Obj 3	FMOLP
Licensed recycling facility-1	New Battery Manufacturer-1	Material Type-1	1,263,900	87,143	127,850	872,470
		Material Type-2	537,740	48,974	0	442,420
		Material Type-3	265,460	1,4053	25,570	214,230
	New Battery Manufacturer-2	Material Type-1	41,344	26,677	0	0
		Material Type-2	96,303	0	51,141	0
		Material Type-3	51,456	27,537	0	0
Licensed recycling facility-2	New Battery Manufacturer-1	Material Type-1	Unopened	0	477,050	0
		Material Type-2		4002.5	275,220	0
		Material Type-3		0	56,267	4343.6
	New Battery Manufacturer-2	Material Type-1		10,006	0	15,931
		Material Type-2		0	0	7240.3
		Material Type-3		2001.2	62,996	0
Licensed recycling facility-3	New Battery Manufacturer-1	Material Type-1	Unopened	634,540	12,558	Unopened
		Material Type-2		290,810	7,245	
		Material Type-3		161,540	0	
	New Battery Manufacturer-2	Material Type-1		0	0	
		Material Type-2		0	0	
		Material Type-3		0	3,1395	
Licensed recycling facility-4	New Battery Manufacturer-1	Material Type-1	Unopened	0	535,900	0
		Material Type-2		1,975	235,930	0
		Material Type-3		0	174,250	0.25
	New Battery Manufacturer-2	Material Type-1		566,740	164,460	416,880
		Material Type-2		289,500	69,867	187,210
		Material Type-3		131,100	0	100,510

tery returns are not available from the all dealers or retailers since the used batteries can be collected from covered dealers only or retailers by the opened collection centres according to the maximum acceptable service distance determined earlier.

6. Sensitivity analysis

In order to investigate the sensitivity of the model and analyzing the sensitivity of decision parameters regarding collection-recovery system to variation of satisfaction degrees related to the each fuzzy goal, the proposed FMOLP problem is resolved with different values of return rate (%), maximum number of opened

facilities for the spent battery collection, recycling capacities (kg) of licensed recycling facilities, respectively.

In the first scenario, low, medium and high rates of returns of each battery type are considered. In the second scenario, variation on the satisfaction degrees of each fuzzy goal is analyzed by changing the maximum number of opened facilities for used battery returns (such as numbers of opened collection centres and/or hybrid facilities). Analyzing the sensitivity by changing capacities of licensed recycling facilities is performed in scenario 3. Sensitivity analysis is applied in three scenarios by using application data as shown in Table 16.

While analyzing the scenarios, different payoff tables were obtained for each run of each scenario. For this reason, limit

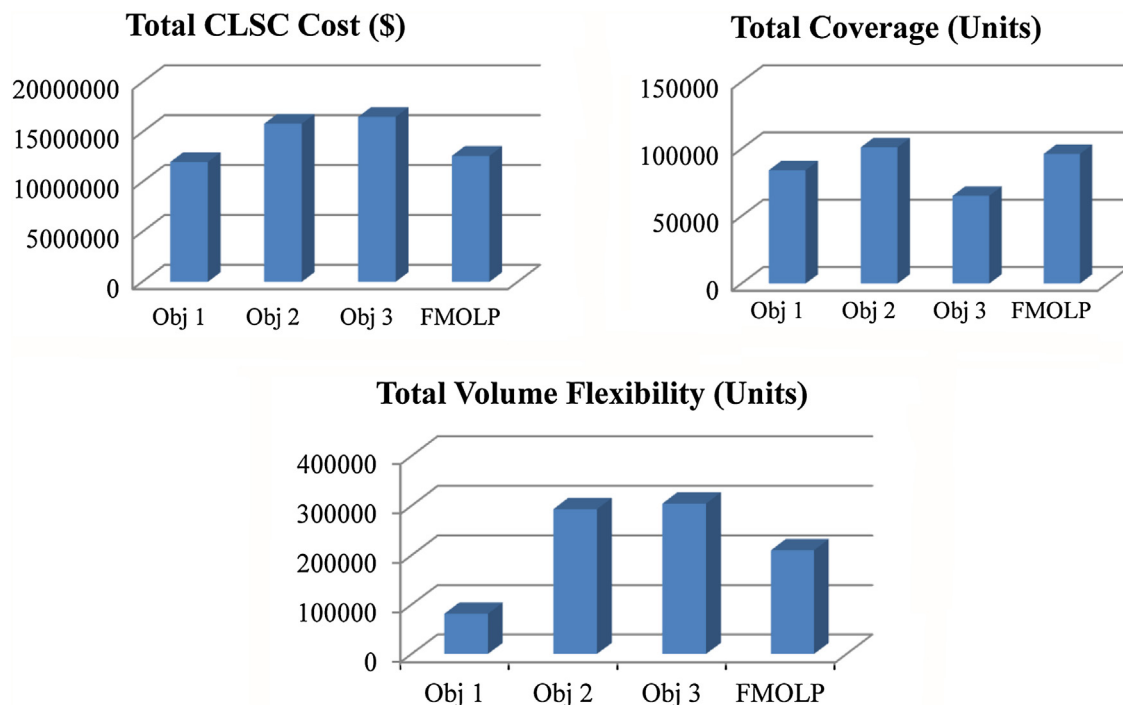


Fig. 13. Comparative analysis of objective values for the optimal individual solutions and FMOLP solution.

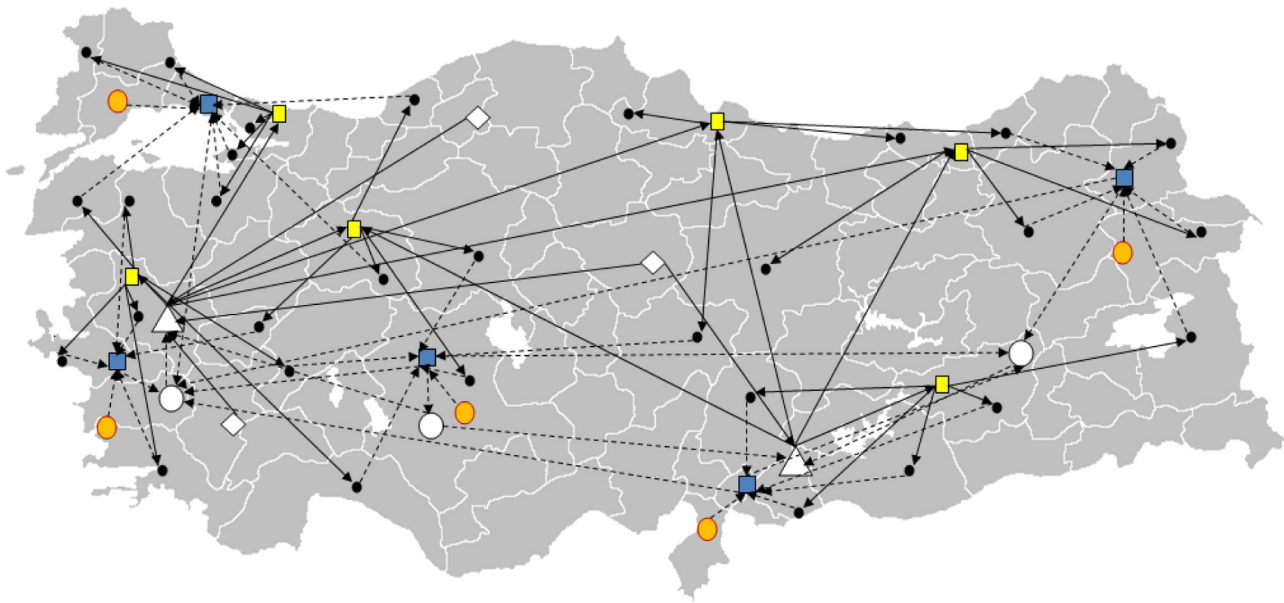


Fig. 14. Optimal forward and reverse network structure considering all objectives simultaneously in the fuzzy environment.

Table 16
Application data of three scenarios.

Scenario	Item	Run 1	Run 2	Run 3
Scenario 1	S_b	Low (40%)	Medium (60%)	High (90%)
Scenario 2	N	4	5	6
Scenario 3	$REcap_{bl}$	350,000 kg	700,000 kg	1,000,000 kg

values of the fuzzy goals were also varied. In other words, since the max-min limits of the fuzzy goals will change in each run of the scenarios, membership functions should be revised for each run of each scenario before applying the scenarios. For instance, limit values of each objective are modified for each run of the each scenario as given Tables 17–19 below. Similarly, membership functions should be reconstructed by using these max-min limit values.

Table 17
Limits of the objectives for each run in scenario 1.

Objectives	Run 1		Run 2		Run 3	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
Total CLSC costs	\$12,414,650	\$16,910,000	\$12,252,795	\$17,614,000	\$11,970,978	\$17,115,000
Total coverage	20,947 units	48,576 units	39,902 units	72,865 units	70,615 units	109,297 units
Total flexibility	80,478 units	304,357 units	81,184 units	304,357 units	81,717 units	304,358 units

Table 18
Limits of the objectives for each run in scenario 2.

Objectives	Run 1		Run 2		Run 3	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
Total CLSC costs	\$12,018,338	\$16,753,000	\$12,018,344	\$17,440,000	\$12,018,339	\$17,368,000
Total coverage	58,612 units	90,965 units	65,181 units	101,157 units	63,910 units	106,504 units
Total flexibility	81,453 units	291,823 units	81,453 units	304,355 units	81,453 units	314,216 units

Table 19
Limits of the objectives for each run in scenario 3.

Objectives	Run 1		Run 2		Run 3	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
Total CLSC costs	\$13,449,304	\$17,410,000	\$12,116,120	\$17,019,000	\$12,080,425	\$18,260,000
Total coverage	61,573 units	101,157 units	65,181 units	101,157 units	60,620 units	101,157 units
Total flexibility	61,886 units	105,605 units	60,891 units	155,609 units	86,526 units	198,466 units

For instance, the lower bound for total CLSC costs will decrease in the case of high return rates as depicted in Table 17. This means that when the cost minimization was taken as single objective, higher return rates yields lower CLSC cost. Additionally, higher return rates increase the coverage as seen from the upper bounds. However, it has no effect on the total flexibility.

The lower bound for total CLSC costs is not affected by the increasing number of opened facilities for the spent battery collection. Also, when maximum number of opened facilities for the spent battery collection is increased, both total coverage and total flexibility increase as well according to the upper bound in Table 18.

As it is seen from Table 19, when the capacities of the licensed recycling facilities are increased, total CLSC cost and total flexibility objectives will improve according to respective lower and upper

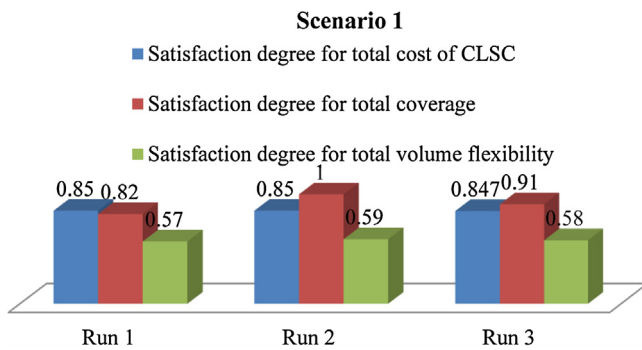


Fig. 15. Satisfaction degrees as results of the scenario 1.

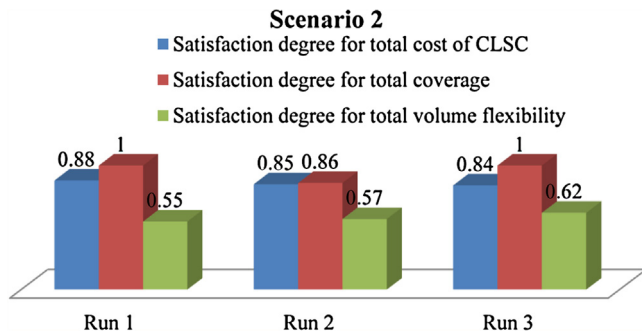


Fig. 16. Satisfaction degrees as results of the scenario 2.

bounds. On the other hand, total coverage is not affected by the capacities of the licensed recycling facilities. These evaluations are based on each objective was considered separately. Results of scenario analysis for simultaneous consideration of objectives can be seen from Figs. 15–17.

Application of the three scenarios in the equivalent crisp formulation of the proposed model yields the following satisfaction degrees for each fuzzy goal as shown in Figs. 15–17.

In the first scenario, different return rates of spent batteries are taken into account. According to the Table 17, higher return rates yield significant cost reduction when the objectives considered independently. However, it is clearly understood from Fig. 15 that higher return rates provide lower or equal costs, higher amounts of spent battery collection (coverage) and equal volume flexibility in the consideration of all fuzzy goals simultaneously.

In the second scenario, effects of the maximum number of opened facilities (collection centres and hybrid facilities) for used battery returns are examined. According to Fig. 16, when the maximum number of opened facilities is increased, total coverage and total volume flexibility will also increase. Moreover, satisfaction

degree for the total cost will not decline too much due to set up one more collection centre or hybrid facility.

Scenario 3 shows that recycling capacity of the licensed recycling facilities has an important impact on the total cost (from \$13,449,304 to \$12,080,425) when only cost minimization objective is taken into account (see in Table 19). On the other hand, increasing in recycling capacity up to a specified level doesn't affect the total coverage. In addition, since the recycling flexibility will grow in case of capacity increases, total volume flexibility always increases as can be seen in Table 19 (from 105,605 units to 198,466 units).

However, in the FMOLP solution, relational satisfaction degree is running low rapidly in the third scenario as it can be seen in Fig. 17. Probably, the most important reason of this decrease is the increase in recycling quantities and decrease in the collection volume flexibility since large amounts of shipments are made from the collection centres/hybrid facilities to licensed recycling facilities. In the third run, satisfaction degree for the total volume flexibility will increase once again because of providing a balance between the forward and reverse flows.

In summary, DMs should act to increase the return rate in order to increase total collection coverage and decrease the total CLSC cost. Furthermore, they may increase the number of opened facilities for the spent battery collection so as to increase both total collection coverage and total flexibility.

7. Conclusion and future research

In this study, a mixed integer linear programming model with fuzzy objectives was developed for a multi-objective, multi-echelon and multi-product CLSC in lead acid battery industry. The proposed model attempts to minimize the total cost of the CLSC, to maximize the collection of returned batteries through the opened collection centres or hybrid facilities and finally to maximize the total volume flexibility which consists of manufacturing/recycling volume flexibility and distribution/collection volume flexibility. For solving the proposed fuzzy multi-objective optimization model, a fuzzy goal programming approach with different goal priorities was used. Determination of the desirable achievement degrees of all fuzzy goals (which is seen as a difficult task in the literature) was achieved by a new approach in a group decision making environment where the importance and optimism characteristics of the group members are different. In order to obtain the weights of the decision makers, fuzzy-AHP method was utilized. Then, overall priority of each fuzzy goal was calculated based on the weighted geometric mean.

In this study, the following contributions are made: (i) Since the scarcity of multi-objective optimization models in the literature of RL & CLSC network design problem, we dealt with an unhandled objective which is the maximization of the collection of returned batteries covered by the opened facilities based on the well known maximal coverage problem in the literature. To the best of our knowledge, this objective has not been addressed by the previous studies so far. This is an important objective in the cases of scarce financial resources as well as different performance measures such as customer satisfaction from the reverse operations (reverse service level), responsiveness of the CLSC configuration, maximum economical benefits obtained from the recovery and environmental effectiveness. (ii) This study also presents the first application of the method developed by Chen and Tsai [6] for fuzzy goal programming with different importance and priorities in RL and CLSC management where the aspiration levels of the objectives should be stated as fuzzy [35]. Thus, a new application area for this method is revealed. In order to produce better decisions than individual decision making and reducing the effects of individual

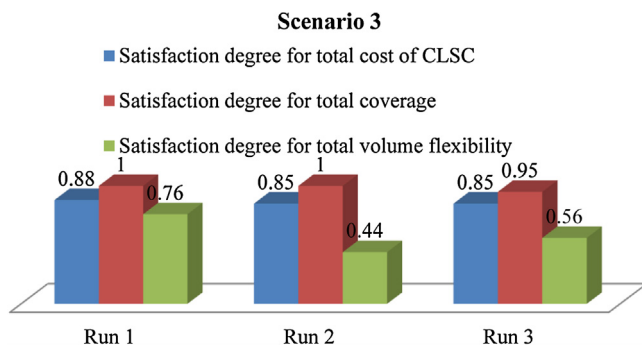


Fig. 17. Satisfaction degrees as results of the scenario 3.

bias, desirable achievement degree of each fuzzy goal is determined in a group decision making environment in this paper where the importance/weights and the index of optimism (*such as moderate, optimistic and pessimistic*) of each group member is different. Because, in such a complex and uncertain CLSC planning and design environment, decisions should be given by the group members who are warranted by the top management. In addition, relative importance or weights of these selected group members may be different for the top management. Besides these different weights, all decision makers have a unique optimistic attitude or character which is also essential in the decision making process. Therefore, this paper proposes a novel fuzzy group decision making approach by integrating Liou and Wang's fuzzy ranking method [49] for handling fuzzy objectives. (iii) New flexibility criteria namely total recycling and collection volume flexibility are added to the predefined objective function, total volume flexibility as an important component due to the nature of RL & CLSC network design problem. (iv) A real life decision making situation in Turkish lead/acid battery industry related to the purchasing and/or selling of spent batteries to the scrap dealers is taken into account in this study. (v) In lead/acid battery sector, decision related to the types of the facilities such as distribution, collection or hybrid that will be opened is as important as where they will be located. Therefore, in addition to determine the facility locations, facility type is also considered in the proposed model for the candidate locations. At the end of the study, the proposed model was validated by a case study which was inspired from the real life battery recovery system in Turkey. Moreover, sensitivity analysis was conducted by using different scenarios regarding the collection-recovery system such as return rate, recycling capacity etc. According to the scenario analysis, when the objectives were treated separately, higher return rates reduced the total cost significantly. On the other hand, both collection coverage and volume flexibility may improve without any cost increment in the case of simultaneous consideration of the goals.

Short and medium term planning models including dynamic cases with multiple time periods, inventory holding, backordering, transportation modes, vehicle types etc. can be developed in the future studies. Therefore, operational planning activities involving routing decisions may also be integrated to the proposed strategic planning model. Additionally, since NP-hardness of the logistics network design problems, development of a meta-heuristic solution approach for larger scale problems can also be planned. This may lead to a number of near optimal solutions within acceptable computational times. Probabilistic demand pattern may also be considered as a future study. In addition to vague goals, some other problem parameters and decision variables may also be stated as fuzzy numbers in the future studies. Thus, different fuzzy mathematical programming techniques may be utilized for fully fuzzified CLSC network design problem under uncertain environments.

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